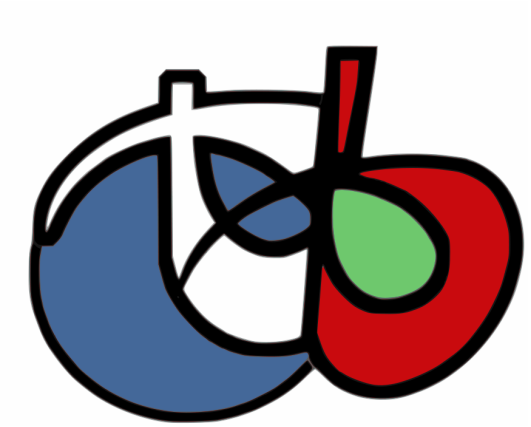
CENTRE NATIONAL D'ÉTUDES SPATIALES

The ORFEO Tool Box Software Guide
Updated for OTB-4.0

OTB Development Team

March 13, 2014

http://www.orfeo-toolbox.org
e-mail: otb@cnes.fr



The ORFEO Toolbox is not a black box.

Ch.D.

FOREWORD

Beside the Pleiades (PHR) and Cosmo-Skymed (CSK) systems developments forming ORFEO, the dual and bilateral system (France - Italy) for Earth Observation, the ORFEO Accompaniment Program was set up, to prepare, accompany and promote the use and the exploitation of the images derived from these sensors.

The creation of a preparatory program[1] is needed because of:

- the new capabilities and performances of the ORFEO systems (optical and radar high resolution, access capability, data quality, possibility to acquire simultaneously in optic and radar),
- the implied need of new methodological developments : new processing methods, or adaptation of existing methods,
- the need to realise those new developments in very close cooperation with the final users for better integration of new products in their systems.

This program was initiated by CNES mid-2003 and will last until mid 2013. It consists in two parts, between which it is necessary to keep a strong interaction:

- A Thematic part,
- A Methodological part.

The Thematic part covers a large range of applications (civil and defence), and aims at specifying and validating value added products and services required by end users. This part includes consideration about products integration in the operational systems or processing chains. It also includes a careful thought on intermediary structures to be developed to help non-autonomous users. Lastly, this part aims at raising future users awareness, through practical demonstrations and validations.

[1] http://smsc.cnes.fr/PLEIADES/A_prog_accomp.htm

The Methodological part objective is the definition and the development of tools for the operational exploitation of the submetric optic and radar images (tridimensional aspects, changes detection, texture analysis, pattern matching, optic radar complementarities). It is mainly based on R&D studies and doctorate and post-doctorate researches.

In this context, CNES[2] decided to develop the *ORFEO ToolBox* (OTB), a set of algorithms encapsulated in a software library. The goals of the OTB is to capitalise a methological *savoir faire* in order to adopt an incremental development approach aiming to efficiently exploit the results obtained in the frame of methodological R&D studies.

All the developments are based on FLOSS (Free/Libre Open Source Software) or existing CNES developments. OTB is distributed under the CéCILL licence, `http://www.cecill.info/licences/Licence_CeCILL_V2-en.html`.

OTB is implemented in C++ and is mainly based on ITK[3] (Insight Toolkit).

[2] http://www.cnes.fr
[3] http://www.itk.org

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Part I

Introduction

CHAPTER

ONE

WELCOME

Welcome to the *ORFEO ToolBox (OTB) Software Guide*.

This document presents the essential concepts used in OTB. It will guide you through the road of learning and using OTB. The Doxygen documentation for the OTB application programming interface is available on line at `http://orfeo-toolbox.sourceforge.net/Doxygen/html`.

1.1 Organization

This software guide is divided into several parts, each of which is further divided into several chapters. Part I is a general introduction to OTB, with—in the next chapter—a description of how to install the ORFEO Toolbox on your computer. Part I also introduces basic system concepts such as an overview of the system architecture, and how to build applications in the C++ programming language. Part II is a short guide with gradual difficulty to get you start programming with OTB. Part III describes the system from the user point of view. Dozens of examples are used to illustrate important system features. Part IV is for the OTB developer. It explains how to create your own classes and extend the system.

1.2 How to Learn OTB

There are two broad categories of users of OTB. First are class developers, those who create classes in C++. The second, users, employ existing C++ classes to build applications. Class developers must be proficient in C++, and if they are extending or modifying OTB, they must also be familiar with OTB's internal structures and design (material covered in Part IV).

The key to learning how to use OTB is to become familiar with its palette of objects and the ways of combining them. We recommend that you learn the system by studying the examples and then, if you are a class developer, study the source code. Start by the first few tutorials in Part II to get

familiar with the build process and the general program organization, follow by reading Chapter 3, which provides an overview of some of the key concepts in the system, and then review the examples in Part III. You may also wish to compile and run the dozens of examples distributed with the source code found in the directory `OTB/Examples`. (Please see the file `OTB/Examples/README.txt` for a description of the examples contained in the various subdirectories.) There are also several hundreds of tests found in the source distribution in `OTB/Testing/Code`, most of which are minimally documented testing code. However, they may be useful to see how classes are used together in OTB, especially since they are designed to exercise as much of the functionality of each class as possible.

1.3 Software Organization

The following sections describe the directory contents, summarize the software functionality in each directory, and locate the documentation and data.

1.3.1 Obtaining the Software

Periodic releases of the software are available on the OTB Web site. These official releases are available a few times a year and announced on the ORFEO Web pages and mailing lists.

This software guide assumes that you are working with the latest official OTB release (available on the OTB Web site).

1.4 Downloading OTB

OTB can be downloaded without cost from the following web site:

`http://www.orfeo-toolbox.org/`

In order to track the kind of applications for which OTB is being used, you will be asked to complete a form prior to downloading the software. The information you provide in this form will help developers to get a better idea of the interests and skills of the toolkit users.

Once you fill out this form you will have access to the download page. This page can be book marked to facilitate subsequent visits to the download site without having to complete any form again.

Then choose the tarball that better fits your system. The options are `.zip` and `.tgz` files. The first type is better suited for MS-Windows while the second one is the preferred format for UNIX systems.

Once you unzip or untar the file, a directory called OTB will be created in your disk and you will be ready for starting the configuration process described in Section 2.2.3 on page 15.

You can also get the current version following instructions in Section 31.3.3, on page 643.

1.4.1 Join the Mailing List

It is strongly recommended that you join the users mailing list. This is one of the primary resources for guidance and help regarding the use of the toolkit. You can subscribe to the users list online at

http://groups.google.com/group/otb-users

The otb-users mailing list is also the best mechanism for expressing your opinions about the toolbox and to let developers know about features that you find useful, desirable or even unnecessary. OTB developers are committed to creating a self-sustaining open-source OTB community. Feedback from users is fundamental to achieving this goal.

1.4.2 Directory Structure

To begin your OTB odyssey, you will first need to know something about OTB's software organization and directory structure. It is helpful to know enough to navigate through the code base to find examples, code, and documentation.

OTB is organized into two different modules. There are the OTB and the OTB-Documents modules. The source code, examples and applications are found in the OTB module; documentation, tutorials, and material related to the design and marketing of OTB are found in OTB-Documents. Usually you will work with the OTB module unless you are a developer, are teaching a course, or are looking at the details of various design documents.

The OTB module contains the following subdirectories:

- OTB/Code—the heart of the software; the location of the majority of the source code.
- OTB/Applications—a set of applications modules that can be launched in different ways (command-line, graphical interface, Python/Java), refer to the OTB Cookbook for more information.
- OTB/CMake—internal files used during the configuration process.
- OTB/Copyright—the copyright information of OTB and all the dependencies included in the OTB source tree.
- OTB/Examples—a suite of simple, well-documented examples used by this guide and to illustrate important OTB concepts.

- OTB/Testing—a large number of small programs used to test OTB. These examples tend to be minimally documented but may be useful to demonstrate various system concepts.
- OTB/Utilities—supporting software for the OTB source code. For example, libraries such as ITK.GDAL.

The source code directory structure—found in OTB/Code—is important to understand since other directory structures (such as the Testing directory) shadow the structure of the OTB/Code directory.

- OTB/Code/ApplicationEngine—the core library for building applications based on OTB.
- OTB/Code/Common—core classes, macro definitions, typedefs, and other software constructs central to OTB.
- OTB/Code/BasicFilters—basic image processing filters.
- OTB/Code/Fusion—image fusion algorithms, as for instance, pansharpening.
- OTB/Code/FeatureExtraction—the location of many feature extraction algorithms.
- OTB/Code/ChangeDetection—a set of remote sensing image change detection algorithms.
- OTB/Code/DisparityMap—tools for estimating disparities – deformations – between images.
- OTB/Code/Fuzzy—fuzzy logic based algorithms, with Dempster-Shafer theory related classes.
- OTB/Code/Hyperspectral—hyperspectral images analysis.
- OTB/Code/IO—classes that support the reading and writing of data.
- OTB/Code/Learning—several functionalities for supervised learning and classification.
- OTB/Code/Markov—implementation of Markov Random Fields regularization and segmentation.
- OTB/Code/MultiScale—a set of functionalities for multiscale image analysis and synthesis.
- OTB/Code/MultiTemporal—time series interpolation related algorithms.
- OTB/Code/OBIA—Object Based Image Analysis filters and data structures.
- OTB/Code/ObjectDetection—Object detection chain based on local feature extraction.
- OTB/Code/Projections—classes allowing to deal with sensor models and cartographic projections.
- OTB/Code/Radiometry—classes allowing to compute vegetation indices and radiometric corrections.

- OTB/Code/SARPolarimetry—some add-ons for SAR polarimetry synthesis and analysis.
- OTB/Code/Segmentation—several functionalities for image segmentation.
- OTB/Code/Simulation—Sensor simulator.
- OTB/Code/SpatialReasoning—several functionalities high level image analysis using spatial reasoning techniques.
- OTB/Code/Testing—internal classes used in the used in the testing framework.
- OTB/Code/Wrappers—wrappers of applications in several access points (command-line, QT Gui, SWIG...).

The OTB-Documents module contains the following subdirectories:

- OTB-Documents/CourseWare—material related to teaching OTB.
- OTB-Documents/Latex—LaTeX styles to produce this work as well as other documents.
- OTB-Documents/SoftwareGuide—LaTeX files used to create this guide. (Note that the code found in OTB/Examples is used in conjunction with these LaTeX files.)

1.4.3 Documentation

Besides this text, there are other documentation resources that you should be aware of.

Doxygen Documentation. The Doxygen documentation is an essential resource when working with OTB. These extensive Web pages describe in detail every class and method in the system. The documentation also contains inheritance and collaboration diagrams, listing of event invocations, and data members. The documentation is heavily hyper-linked to other classes and to the source code. The Doxygen documentation is available on-line at http://www.orfeo-toolbox.org/doxygen/.

Header Files. Each OTB class is implemented with a .h and .cxx/.txx file (.txx file for templated classes). All methods found in the .h header files are documented and provide a quick way to find documentation for a particular method. (Indeed, Doxygen uses the header documentation to produces its output.)

1.4.4 Data

The OTB Toolkit was designed to support the ORFEO Acompaniment Program and its associated data. This data is available at http://smsc.cnes.fr/PLEIADES/index.htm.

1.5 The OTB Community and Support

OTB was created from its inception as a collaborative, community effort. Research, teaching, and commercial uses of the toolkit are expected. If you would like to participate in the community, there are a number of possibilities.

- Users may actively report bugs, defects in the system API, and/or submit feature requests. Currently the best way to do this is through the OTB users mailing list.
- Developers may contribute classes or improve existing classes. If you are a developer, you may request permission to join the OTB developers mailing list. Please do so by sending email to otb "at" cnes.fr. To become a developer you need to demonstrate both a level of competence as well as trustworthiness. You may wish to begin by submitting fixes to the OTB users mailing list.
- Research partnerships with members of the ORFEO Acompaniment Program are encouraged. CNES will encourage the use of OTB in proposed work and research projects.
- Educators may wish to use OTB in courses. Materials are being developed for this purpose, e.g., a one-day, conference course and semester-long graduate courses. Watch the OTB web pages or check in the `OTB-Documents/CourseWare` directory for more information.

1.6 A Brief History of OTB

Beside the Pleiades (PHR) and Cosmo-Skymed (CSK) systems developments forming ORFEO, the dual and bilateral system (France - Italy) for Earth Observation, the ORFEO Accompaniment Program was set up, to prepare, accompany and promote the use and the exploitation of the images derived from these sensors.

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In this context, CNES[2] decided to develop the *ORFEO ToolBox* (OTB), a set of algorithms encapsulated in a software library. The goals of the OTB is to capitalise a methological *savoir faire* in order to adopt an incremental development approach aimin to efficiently exploit the results obtained in the frame of methodological R&D studies.

All the developments are based on FLOSS (Free/Libre Open Source Software) or existing CNES developments.

OTB is implemented in C++ and is mainly based on ITK[3] (Insight Toolkit):

- ITK is used as the core element of OTB
- OTB classes inherit from ITK classes
- The software development procedure of OTB is strongly inspired from ITK's (Extreme Programming, test-based coding, Generic Programming, etc.)
- The documentation production procedure is the same as for ITK
- Several chapters of the Software Guide are litterally copied from ITK's Software Guide (with permission).
- Many examples are taken from ITK.

1.6.1 ITK's history

In 1999 the US National Library of Medicine of the National Institutes of Health awarded six three-year contracts to develop an open-source registration and segmentation toolkit, that eventually came to be known as the Insight Toolkit (ITK) and formed the basis of the Insight Software

[2] http://www.cnes.fr
[3] http://www.itk.org

Consortium. ITK's NIH/NLM Project Manager was Dr. Terry Yoo, who coordinated the six prime contractors composing the Insight consortium. These consortium members included three commercial partners—GE Corporate R&D, Kitware, Inc., and MathSoft (the company name is now Insightful)—and three academic partners—University of North Carolina (UNC), University of Tennessee (UT) (Ross Whitaker subsequently moved to University of Utah), and University of Pennsylvania (UPenn). The Principle Investigators for these partners were, respectively, Bill Lorensen at GE CRD, Will Schroeder at Kitware, Vikram Chalana at Insightful, Stephen Aylward with Luis Ibáñez at UNC (Luis is now at Kitware), Ross Whitaker with Josh Cates at UT (both now at Utah), and Dimitri Metaxas at UPenn (now at Rutgers). In addition, several subcontractors rounded out the consortium including Peter Raitu at Brigham & Women's Hospital, Celina Imielinska and Pat Molholt at Columbia University, Jim Gee at UPenn's Grasp Lab, and George Stetten at the University of Pittsburgh.

In 2002 the first official public release of ITK was made available.

CHAPTER

TWO

INSTALLATION

This section describes the process for installing OTB on your system. OTB is a toolbox, and as such, once it is installed in your computer, it provides by default a set of useful libraries. You can use these libraries to build your own applications based on it. What OTB does provide, besides the toolbox, is a large set of test files and examples that will introduce you to OTB concepts and will show you how to use OTB in your own projects.

Since the release 3.12, OTB embeds a specific framework to generate applications in a more user-friendly way. OTB provides for each application one shared library (also known as plugin). This plugin can be auto-loaded into appropriate tools without recompiling, and is able to fully describe its own parameters, behavior and documentation.

The tools to use these plugins can be extended, but OTB is shipped with the following:

- A command-line launcher,
- A graphical launcher, with an auto-generated Qt interface, providing ergonomic parameters setting, display of documentation, and progress reporting,
- A C and SWIG interface, which means that any application can be loaded, set up and executed into a high-level language such as **Python** for instance.

Based on a visualization framework which used FLTK libraries, Orfeo ToolBox team provides an integrated application which giving graphical access to a lot of OTB functionalities: **Monteverdi**. Since mid-2013, we also provide a new graphical application based on Qt: **Monteverdi2**. This new application used the OTB-Applications tools as processing framework.

There are two ways to install OTB library on your system: installing from a binary distribution or compiling from sources. The choice depends on your system, and on what you intend to do.

2.1 Installing binary packages

You can find all information about the installation of binary packages for OTB-Applications, Monteverdi and Monteverdi2 (if they are available on your platform) into the OTB-Cookbook.

The binary packages for OTB library are only available on:

- Ubuntu 12.04 and higher
- OpenSuse 12.X and higher
- MacOSX through MacPorts software

Currently, no OSGeo4W package is available for the OTB library, you need to build from source to use it on windows platform. However you can fund binary packages for Monteverdi, Monteverdi2 and OTB-Applications (command-line, QT based and python ones).

2.2 Building from sources

OTB has been developed and tested across different combinations of operating systems, compilers, and hardware platforms including MS-Windows, Linux on Intel-compatible hardware and Mac OSX. It is known to work with the following compilers in 32/64 bit:

- Visual Studio 2010 and higher compiler on MS-Windows
- GCC 4.1 and higher on Unix/Linux systems
- GCC on MacOSX (10.8 and higher) systems

Given the advanced usage of C++ features in the toolbox, some compilers may have difficulties processing the code. If you are currently using an outdated compiler this may be an excellent excuse for upgrading this old piece of software!

Please note that even if this section only describes how to compile OTB library and applications from sources, Monteverdi1 and Monteverdi2 can be compiled in a similar way.

In order to compile and install OTB, you need on your system:

- CMake software (binary packages are available for most platforms).
- a compilers of the previous list.

2.2.1 Which libraries/packages are needed before compiling and installing OTB?

The following table gathered the libraries (mandatory or not) used in the OTB. Some of them are included in the OTB but can be used as external libraries (this the default behavior if they are detected on your platform).

Library	Web site	Mandatory	Where	Minimum version
ITK	http://www.itk.org	yes	Intern/**Extern**	4.5.0
GDAL	http://www.gdal.org	yes	Extern	1.10
OSSIM	http://www.ossim.org	yes	**Intern**/Extern	1.8.6
Curl	http://www.curl.haxx.se	no	Extern	-
FFTW	http://www.fftw.org	no	Extern	-
expat	http://expat.sourceforge.net/	yes	Intern/**Extern**	-
libtiff	http://www.libtiff.org	yes	Extern	-
libgeotiff	http://trac.osgeo.org/geotiff/	yes	Extern	-
OpenJPEG	http://code.google.com/p/openjpeg/	no	Intern	-
boost	http://www.boost.org	no	Intern/**Extern**	-
openthreads	http://www.openscenegraph.org	no	Intern/**Extern**	-
Mapnik	http://www.mapnik.org	no	Extern	-
tinyXML	http://www.grinninglizard.com/tinyxml	yes	Intern/**Extern**	-
KML	http://libkml.googlecode.com	yes	Intern/**Extern**	-
6S	http://6s.ltdri.org	yes	Intern	-
edison	http://www.caip.rutgers.edu/riul/	yes	Intern	-
SiftFast	http://libsift.sourceforge.net	yes	Intern	-
MuParser	http://www.muparser.sourceforge.net	yes	Intern/**Extern**	-
libSVM	http://www.csie.ntu.edu.tw/~cjlin/libsvm	yes	Intern	-
Qt	http://qt-project.org/	no	Extern	4

Table 2.1: Libraries used in the OTB. In the column Where, the default behavior during the configuration of OTB is indicated by when the status is bold. For example, by default external ITK library is used.

For windows user, some of these libraries can be found into the OSGeo4W installer.

For Monteverdi, in addition to OTB, FLTK is required (http://www.fltk.org) as an external dependency. Therefore, you need to install it from your package manager or build it from source. For windows users, you can find it through the OSGeo4W installer.

For Monteverdi2, in addition to OTB, Qt4 (http://qt-project.org/) and Qwt5 (http://qwt.sourceforge.net/) are required as external dependencies. Therefore, you

need to install them from your package manager or build them from source. For windows users, you can find them through the OSGeo4W installer.

You can find all the information to get and install these libraries directly from their respective website.

2.2.2 Getting the OTB source code

There are three ways of getting the OTB source code:

- Download the latest current release from the OTB download page,
- Clone the current release with Mercurial from the OTB mercurial server,
- Clone the latest revision with Mercurial from the OTB mercurial server.

These last two options need a proper Mercurial installation. To get source code from Mercurial, do:

```
hg clone http://hg.orfeo-toolbox.org/OTB
```

Using Mercurial, you can easily navigate through the different version. For instance, this brings you to the 3.16.0 source code version:

```
hg update -r 3.16.0
```

And this brings you to the latest development version:

```
hg update
```

2.2.3 Configuring OTB

The challenge of supporting OTB across platforms has been solved through the use of CMake, a cross-platform, open-source build system. CMake is used to control the software compilation process using simple platform and compiler independent configuration files. CMake generates native makefiles and workspaces that can be used in the compiler environment of your choice. CMake is quite sophisticated: it supports complex environments requiring system configuration, compiler feature testing, and code generation.

CMake generates Makefiles under UNIX systems and generates Visual Studio workspaces under Windows (and appropriate build files for other compilers like Borland). The information used by CMake is provided by `CMakeLists.txt` files that are present in every directory of the OTB source tree. These files contain information that the user provides to CMake at configuration time. Typical information includes paths to utilities in the system and the selection of software options specified by the user.

Preparing CMake

CMake can be downloaded at no cost from

`http://www.cmake.org`

OTB requires at least CMake version 2.8.6. You can download binary versions for most of the popular platforms including Windows, Solaris, IRIX, HP, Mac and Linux. Alternatively you can download the source code and build CMake on your system. Follow the instructions in the CMake Web page for downloading and installing the software.

Running CMake initially requires that you provide two pieces of information:

- Where the source code directory is located (ex.: OTB_SOURCE_DIR),
- Where the object code is to be produced: (ex.: OTB_BINARY_DIR).

These are referred to as the *source directory* and the *binary directory*. We recommend setting the binary directory to be different than the source directory (an *out-of-source* build), but OTB will still build if they are set to a directory inside the source directory (an *in-source* build).

Compiling OTB

CMake runs in an interactive mode in that you iteratively select options and configure according to these options. The iteration proceeds until no more options remain to be selected. At this point, a generation step produces the appropriate build files for your configuration.

This interactive configuration process can be better understood if you imagine that you are walking through a decision tree. Every option that you select introduces the possibility that new, dependent options may become relevant. These new options are presented by CMake at the top of the options list in its interface. Only when no new options appear after a configuration iteration can you be sure that the necessary decisions have all been made. At this point build files are generated for the current configuration.

As the following figures display it, CMake has a different interface according to your systems.

On Windows:

The OTB needs some external libraries to work, as described in the table 2.1. To manage correctly and easily the dependencies of OTB under Windows we strongly recommend to install OSGeo4W tool. This software will provide you with all the necessary dependencies in 32 bit and 64 bit mode. Please follow these steps:

1. Download the installer setup (32/64bit)
2. Run the setup installer with Admin Rights

3. Select Advanced Install
4. Select Install from Internet
5. Keep as much as possible the default values about root directory and other parameters. You must have the write access to this root directory.
6. In the next screen, select a local package directory (idem you must have the write access to this directory)
7. Select your Internet connection settings
8. Select the default download site
9. Select the following packages:
    - msvcrt
    - gdal
    - curl
    - expat
    - ossim
    - opencv
    - qt4-devel
    - swig
    - python
    - fftw-devel
    - libtiff
10. Run the installation process
11. Accept all the dependencies required by the selected packages
12. Wait the downloading and the installation of the packages

Create a directory, where you have write access, to store your work (for example at C:\path\to\MyOTBDir). Organize your directories as it :

- MyOTBDir\src
- MyOTBDir\build
- MyOTBDir\install

Retrieve the latest release of OTB (you can find the latest source here) and unzip it into the previous source directory.

We will describe here how to compile and install the library with the main functionalities in Release and ReleaseWithDebugInfo mode. Create an OTB.bat file into your MyOTBDir and copy paste the following lines:

```
@echo off

call "C:\Program Files (x86)\Microsoft Visual Studio 10.0\Common7\Tools\vsvars32.bat"

set /A ARGS_COUNT=0
for %%A in (%*) do set /A ARGS_COUNT+=1
if %ARGS_COUNT% NEQ 3 (goto :Usage)

if NOT DEFINED OSGEO4W_ROOT (goto :NoOSGEO4W)

set src_dir=%1
set build_dir=%2
set otb_install_dir=%3
set current_dir=%CD%

set LANG=C
set ITK_AUTOLOAD_PATH=
set PYTHONPATH=
set PATH=%OSGEO4W_ROOT%\apps\swigwin\;%PATH%

cd %build_dir%

cmake  %src_dir% ^
-G "Visual Studio 10" ^
-DBUILD_EXAMPLES:BOOL=ON ^
-DOTB_WRAP_QT:BOOL=ON ^
-DOTB_WRAP_PYTHON:BOOL=ON ^
-DPYTHON_LIBRARY:FILEPATH="%OSGEO4W_ROOT%/apps/Python27/libs/python27.lib" ^
-DPYTHON_INCLUDE_DIR:PATH="%OSGEO4W_ROOT%/apps/Python27/include" ^
-DPYTHON_EXECUTABLE:FILEPATH="%OSGEO4W_ROOT%/bin/python.exe" ^
-DOTB_USE_OPENCV:BOOL=ON ^
-DCMAKE_INSTALL_PREFIX:PATH=%otb_install_dir% ^
-DCMAKE_CONFIGURATION_TYPES:STRING=Release;RelWithDebInfo

cmake --build . --target INSTALL --config RelWithDebInfo

cd %current_dir%
```

```
goto :END

:Usage
echo You need to provide 3 arguments to the script:
echo   1. path to the source directory
echo   2. path to the build directory (an empty directory)
echo   3. path to the installation directory (an empty directory)
GOTO :END

:NoOSGEO4W
echo You need to run this script from an OSGeo4W shell
GOTO :END

:END
```

Into a OSGEo4W shell, run the OTB.bat with the right arguments: full path to the OTB src directory, full path to the OTB build directory, full path to the place where install OTB. Take a break, you made it: OTB is installed in your install directory (should be C:\path\to\MyOTBDir\install). If you want test: into an OSGeo4W shell, go to the bin directory of the install directory and run HelloWorld.exe. If you want build OTB in Release config, into the OSGeo4W shell, open the OTB.sln and select this configuration from the configuration selector and build the solution.

If you want use more recent MS-compiler please change the path to vsvars32.bat file and change the generator used by cmake line. OTB should support compilation under Visual Studio 2012 and 2013.

That should be all! Otherwise, subscribe to otb-users@googlegroups.com and you will get some help.

On Linux/Unix: On Unix, the binary directory is created by the user and CMake is invoked with the path to the source directory. For example:

```
mkdir OTB_BINARY_DIR
cd OTB_BINARY_DIR
ccmake ../OTB_SOURCE_DIR
```

Once the interface open, you can push *c* (for Configure), or/and *t* for Toggle (to have access to the advanced variables). If you have follow the previous section every needed libraries are in the */usr* and will be found automatically by CMake. Set the following recommended CMake variables:

- OTB_USE_EXTERNAL_BOOST:BOOL=ON
- OTB_USE_CURL:BOOL=ON
- OTB_USE_EXTERNAL_EXPAT:BOOL=ON
- OTB_USE_JPEG2000:BOOL=ON

Push *c* to update CMake until the option *Generate* is accessible in the GUI, then push *g* fot *Generate*. The CMake interface will close itself. Then, go into your build directory (here OTB_BINARY_DIR) and do *make* to launch the compilation.

If you want to put OTB in a standard location, you can proceed with:

```
make install
```

Compilation awarness The build process will typically take anywhere from 15 to 30 minutes depending on the performance of your system. If you decide to enable testing as part of the normal build process, about 2500 small tests programs will be compiled. This will verify that the basic components of OTB have been correctly built on your system.

Set the CMake variables `BUILD_TESTING` and `BUILD_EXAMPLES` to ON will activate the compilation of the examples and the tests and slow down the build process. The examples distributed with the toolbox are a helpful resource for learning how to use OTB components but are not essential for the use of the toolbox itself. The testing section includes a large number of small programs that exercise the capabilities of OTB classes. Due to the large number of tests, enabling the testing option will considerably increase the build time. It is not desirable to enable this option for a first build of the toolbox.

Set the CMake variable `BUILD_APPLICATION` to ON will activate the compilation of the applications and their launchers needed to use it. A complete list of these applications, described in the OTB Cookbook, can be found on OTB Website.

2.3 Getting Started With OTB

The simplest way to create a new project with OTB is to create a new directory somewhere in your disk and create two files in it. The first one is a `CMakeLists.txt` file that will be used by CMake to generate a Makefile (if you are using UNIX) or a Visual Studio workspace (if you are using MS-Windows). The second file is an actual C++ program that will exercise some of the large number of classes available in OTB. The details of these files are described in the following section. Under Windows, we provide a specifc example to show you how to proceed.

For Unix users, once both files are in your directory you can run CMake in order to configure your project. Under UNIX, you can cd to your newly created directory and type "`ccmake .`". Note the "." in the command line for indicating that the `CMakeLists.txt` file is in the current directory. The curses interface will require you to provide the directory where OTB was built. This is the same path that you indicated for the `OTB_BINARY_DIR` variable at the time of configuring OTB. Then CMake will require you to provide the path to the binary directory where OTB was built. The OTB binary directory will contain a file named `OTBConfig.cmake` generated during the configuration process at the time OTB was built. From this file, CMake will recover all the information required to configure your new OTB project.

2.3.1 Hello World !

This section is dedicated to Unix or Linux or MacOsX users, the next section provide specific information for Windows users.

Here is the content of the two files to write in your new project. These two files can be found in the `OTB/Examples/Installation` directory. The `CMakeLists.txt` file contains the following lines:

```
PROJECT(HelloWorld)

FIND_PACKAGE(OTB REQUIRED)
INCLUDE(${OTB_USE_FILE})

ADD_EXECUTABLE(HelloWorld HelloWorld.cxx )
TARGET_LINK_LIBRARIES(HelloWorld OTBIO)
```

The first line defines the name of your project. The second line loads a CMake file with a predefined strategy for finding OTB [1]. If the strategy for finding OTB fails, CMake will prompt you for the directory where OTB is installed in your system. In that case you will write this information in the `OTB_DIR` variable. The line `INCLUDE(${USE_OTB_FILE})` loads the `UseOTB.cmake` file to set all the configuration information from OTB.

The line `ADD_EXECUTABLE` defines as its first argument the name of the executable that will be produced as result of this project. The remaining arguments of `ADD_EXECUTABLE` are the names of the source files to be compiled and linked. Finally, the `TARGET_LINK_LIBRARIES` line specifies which OTB libraries will be linked against this project.

The source code for this example can be found in the file `Examples/Installation/HelloWorld.cxx`.

The following code is an implementation of a small OTB program. It tests including header files and linking with OTB libraries.

```
#include "otbImage.h"
#include <iostream>

int main()
{
  typedef otb::Image<unsigned short, 2> ImageType;

  ImageType::Pointer image = ImageType::New();

  std::cout << "OTB Hello World !" << std::endl;

  return EXIT_SUCCESS;
}
```

[1] Similar files are provided in CMake for other commonly used libraries, all of them named `Find*.cmake`

This code instantiates an image whose pixels are represented with type `unsigned short`. The image is then constructed and assigned to a `itk::SmartPointer`. Although later in the text we will discuss `SmartPointer`'s in detail, for now think of it as a handle on an instance of an object (see section 3.2.4 for more information). The `itk::Image` class will be described in Section 5.1.

At this point you have successfully installed and compiled OTB, and created your first simple program. If you have difficulties, please join the otb-users mailing list (Section 1.4.1 on page 5) and post questions there.

2.3.2 Build your first application based on the OTB library on Windows platform

Create a directory (with write access) where to store your work (for example at C:\path\to\MyFirstCode). Organize your repository as it :

- MyFirstCode\src
- MyFirstCode\build

Follow the following steps:

1. Create a CMakeLists.txt into the src repository with the following lines:

```
project(MyFirstProcessing)

cmake_minimum_required(VERSION 2.8)

find_package(OTB REQUIRED)
include(${OTB_USE_FILE})

add_executable(MyFirstProcessing MyFirstProcessing.cxx )

target_link_libraries(MyFirstProcessing OTBCommon OTBIO )
```

2. Create a MyFirstProcessing.cxx into the src repository with the following lines:

```
#include "otbImage.h"
#include "otbVectorImage.h"
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
#include "otbMultiToMonoChannelExtractROI.h"

int main(int argc, char* argv[])
```

```
{
  if (argc < 3)
  {
    std::cerr << "Usage: " << std::endl;
    std::cerr << argv[0] << "  inputImageFile  outputImageFile" << std::endl;
    return EXIT_FAILURE;
  }

  typedef unsigned short PixelType;
  typedef otb::Image <PixelType, 2> ImageType;
  typedef otb::VectorImage <PixelType, 2> VectorImageType;
  typedef otb::MultiToMonoChannelExtractROI <PixelType, PixelType> FilterType;
  typedef otb::ImageFileReader<VectorImageType> ReaderType;
  typedef otb::ImageFileWriter<ImageType> WriterType;

  FilterType::Pointer filter = FilterType::New();
  ReaderType::Pointer reader = ReaderType::New();
  WriterType::Pointer writer = WriterType::New();

  reader->SetFileName(argv[1]);
  filter->SetInput(reader->GetOutput());
  writer->SetFileName(argv[2]);
  writer->SetInput(filter->GetOutput());

  return EXIT_SUCCESS;
}
```

3. create a file named BuildMyFirstProcessing.bat into the MyFirstCode directory with the following lines:

```
@echo off

set /A ARGS_COUNT=0
for %%A in (%*) do set /A ARGS_COUNT+=1
if %ARGS_COUNT% NEQ 3 (goto :Usage)

if NOT DEFINED OSGEO4W_ROOT (goto :NoOSGEO4W)

set src_dir=%1
set build_dir=%2
set otb_install_dir=%3
set current_dir=%CD%

cd %build_dir%
```

```
cmake %src_dir% ^
      -DCMAKE_INCLUDE_PATH:PATH="%OSGEO4W_ROOT%\include" ^
      -DCMAKE_LIBRARY_PATH:PATH="%OSGEO4W_ROOT%\lib" ^
      -DOTB_DIR:PATH=%otb_install_dir% ^
      -DCMAKE_CONFIGURATION_TYPES:STRING=Release

cmake --build . --target INSTALL --config Release

cd %current_dir%

goto :END

:Usage
echo You need to provide 3 arguments to the script:
echo   1. path to the source directory
echo   2. path to the build directory
echo   3. path to the installation directory
GOTO :END

:NoOSGEO4W
echo You need to run this script from an OSGeo4W shell
GOTO :END

:END
```

4. into a OSGEo4W shell, run the configure.bat with the right arguments: full path to your src directory, full path to your build directory, full path to the place where find OTBConfig.cmake file (should be C:\path\to\MyOTBDir\install\lib\otb).
5. into the OSGeo4W shell, open the MyFirstProcessing.sln
6. build the solution
7. into the OSGeo4W shell, go to the bin\Release directory and run MyFirstProcessing.exe. You can try for example with the otb_logo.tif file which can be found into the OTB source.

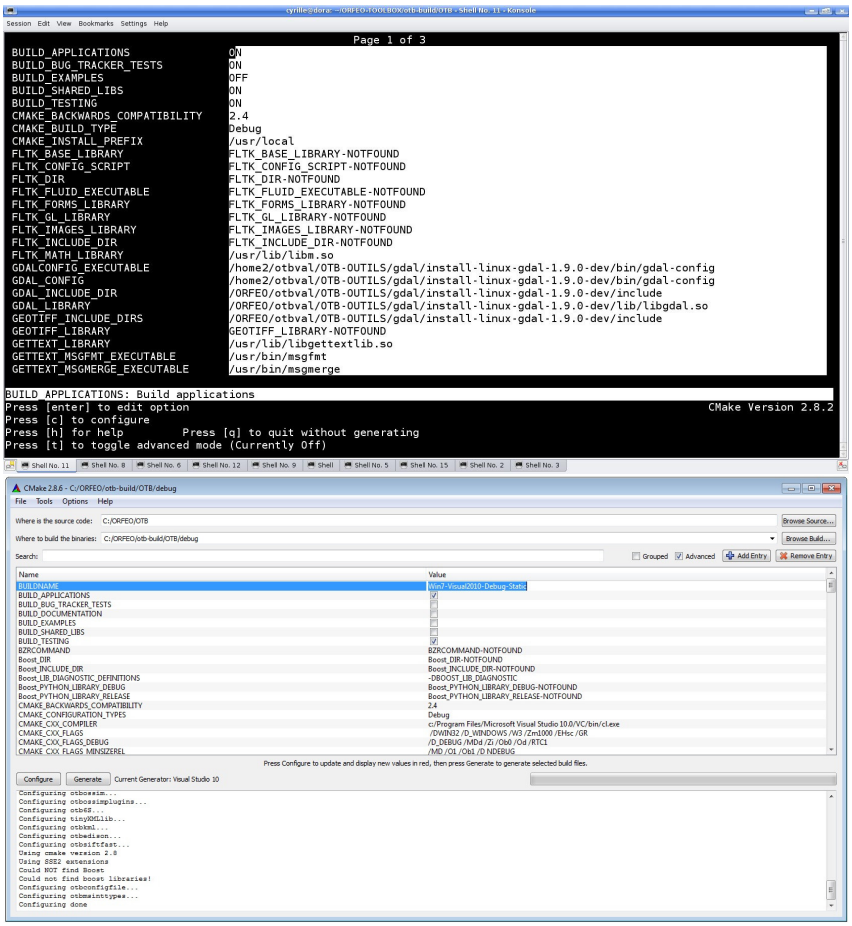


Figure 2.1: CMake interface. Top) `ccmake`, the UNIX version based on `curses`. Bottom) `CMakeSetup`, the MS-Windows version based on MFC.

CHAPTER

THREE

SYSTEM OVERVIEW

The purpose of this chapter is to provide you with an overview of the *ORFEO Toolbox* system. We recommend that you read this chapter to gain an appreciation for the breadth and area of application of OTB. In this chapter, we will make reference either to *OTB features* or *ITK features* without distinction. Bear in mind that OTB uses ITK as its core element, so all the fundamental elements of OTB come from ITK. OTB extends the functionalities of ITK for the remote sensing image processing comunity. We benefit from the Open Source development approach chosen for ITK, which allows us to provide an impressive set of functionalities with much lesser effort than it would have been the case in a closed source universe!

3.1 System Organization

The ORFEO Toolbox consists of several subsystems. A brief description of these subsystems follows. Later sections in this chapter—and in some cases additional chapters—cover these concepts in more detail. (Note: in the previous chapter, another module—`OTB-Documents` is briefly described.)

Essential System Concepts. Like any software system, OTB is built around some core design concepts. OTB uses those of ITK. Some of the more important concepts include generic programming, smart pointers for memory management, object factories for adaptable object instantiation, event management using the command/observer design paradigm, and multithreading support.

Numerics OTB, as ITK uses VXL's VNL numerics libraries. These are easy-to-use C++ wrappers around the Netlib Fortran numerical analysis routines (`http://www.netlib.org`).

Data Representation and Access. Two principal classes are used to represent data: the `otb::Image` and `itk::Mesh` classes. In addition, various types of iterators and containers are used in ITK to hold and traverse the data. Other important but less popular classes are also used to represent data such as histograms.

ITK's Data Processing Pipeline. The data representation classes (known as *data objects*) are operated on by *filters* that in turn may be organized into data flow *pipelines*. These pipelines maintain state and therefore execute only when necessary. They also support multi-threading, and are streaming capable (i.e., can operate on pieces of data to minimize the memory footprint).

IO Framework. Associated with the data processing pipeline are *sources*, filters that initiate the pipeline, and *mappers*, filters that terminate the pipeline. The standard examples of sources and mappers are *readers* and *writers* respectively. Readers input data (typically from a file), and writers output data from the pipeline. *Viewers* are another example of mappers.

Spatial Objects. Geometric shapes are represented in OTB using the ITK spatial object hierarchy. These classes are intended to support modeling of anatomical structures in ITK. OTB uses them in order to model cartographic elements. Using a common basic interface, the spatial objects are capable of representing regions of space in a variety of different ways. For example: mesh structures, image masks, and implicit equations may be used as the underlying representation scheme. Spatial objects are a natural data structure for communicating the results of segmentation methods and for introducing geometrical priors in both segmentation and registration methods.

ITK's Registration Framework. A flexible framework for registration supports four different types of registration: image registration, multiresolution registration, PDE-based registration, and FEM (finite element method) registration.

FEM Framework. ITK includes a subsystem for solving general FEM problems, in particular non-rigid registration. The FEM package includes mesh definition (nodes and elements), loads, and boundary conditions.

Level Set Framework. The level set framework is a set of classes for creating filters to solve partial differential equations on images using an iterative, finite difference update scheme. The level set framework consists of finite difference solvers including a sparse level set solver, a generic level set segmentation filter, and several specific subclasses including threshold, Canny, and Laplacian based methods.

Wrapping. ITK uses a unique, powerful system for producing interfaces (i.e., "wrappers") to interpreted languages such as Tcl and Python. The GCC_XML tool is used to produce an XML description of arbitrarily complex C++ code; CSWIG is then used to transform the XML description into wrappers using the SWIG package. OTB does not use this system at present.

3.2 Essential System Concepts

This section describes some of the core concepts and implementation features found in ITK and therefore also in OTB.

3.2.1 Generic Programming

Generic programming is a method of organizing libraries consisting of generic—or reusable—software components [95]. The idea is to make software that is capable of "plugging together" in an efficient, adaptable manner. The essential ideas of generic programming are *containers* to hold data, *iterators* to access the data, and *generic algorithms* that use containers and iterators to create efficient, fundamental algorithms such as sorting. Generic programming is implemented in C++ with the *template* programming mechanism and the use of the STL Standard Template Library [7].

C++ templating is a programming technique allowing users to write software in terms of one or more unknown types `T`. To create executable code, the user of the software must specify all types `T` (known as *template instantiation*) and successfully process the code with the compiler. The `T` may be a native type such as `float` or `int`, or `T` may be a user-defined type (e.g., `class`). At compile-time, the compiler makes sure that the templated types are compatible with the instantiated code and that the types are supported by the necessary methods and operators.

ITK uses the techniques of generic programming in its implementation. The advantage of this approach is that an almost unlimited variety of data types are supported simply by defining the appropriate template types. For example, in OTB it is possible to create images consisting of almost any type of pixel. In addition, the type resolution is performed at compile-time, so the compiler can optimize the code to deliver maximal performance. The disadvantage of generic programming is that many compilers still do not support these advanced concepts and cannot compile OTB. And even if they do, they may produce completely undecipherable error messages due to even the simplest syntax errors. If you are not familiar with templated code and generic programming, we recommend the two books cited above.

3.2.2 Include Files and Class Definitions

In ITK and OTB classes are defined by a maximum of two files: a header `.h` file and an implementation file—`.cxx` if a non-templated class, and a `.txx` if a templated class. The header files contain class declarations and formatted comments that are used by the Doxygen documentation system to automatically produce HTML manual pages.

In addition to class headers, there are a few other important header files.

`itkMacro.h` is found in the `Utilities/ITK/Code/Common` directory and defines standard system-wide macros (such as `Set/Get`, constants, and other parameters).

`itkNumericTraits.h` is found in the `Utilities/ITK/Code/Common` directory and defines numeric characteristics for native types such as its maximum and minimum possible values.

`itkWin32Header.h` is found in the `Utilities/ITK/Code/Common` and is used to define operating system parameters to control the compilation process.

3.2.3 Object Factories

Most classes in OTB are instantiated through an *object factory* mechanism. That is, rather than using the standard C++ class constructor and destructor, instances of an OTB class are created with the static class `New()` method. In fact, the constructor and destructor are `protected:` so it is generally not possible to construct an OTB instance on the heap. (Note: this behavior pertains to classes that are derived from `itk::LightObject`. In some cases the need for speed or reduced memory footprint dictates that a class not be derived from LightObject and in this case instances may be created on the heap. An example of such a class is `itk::EventObject`.)

The object factory enables users to control run-time instantiation of classes by registering one or more factories with `itk::ObjectFactoryBase`. These registered factories support the method `CreateInstance(classname)` which takes as input the name of a class to create. The factory can choose to create the class based on a number of factors including the computer system configuration and environment variables. For example, in a particular application an OTB user may wish to deploy their own class implemented using specialized image processing hardware (i.e., to realize a performance gain). By using the object factory mechanism, it is possible at run-time to replace the creation of a particular OTB filter with such a custom class. (Of course, the class must provide the exact same API as the one it is replacing.) To do this, the user compiles her class (using the same compiler, build options, etc.) and inserts the object code into a shared library or DLL. The library is then placed in a directory referred to by the `OTB_AUTOLOAD_PATH` environment variable. On instantiation, the object factory will locate the library, determine that it can create a class of a particular name with the factory, and use the factory to create the instance. (Note: if the `CreateInstance()` method cannot find a factory that can create the named class, then the instantiation of the class falls back to the usual constructor.)

In practice object factories are used mainly (and generally transparently) by the OTB input/output (IO) classes. For most users the greatest impact is on the use of the `New()` method to create a class. Generally the `New()` method is declared and implemented via the macro `itkNewMacro()` found in `Utilities/ITK/Common/itkMacro.h`.

3.2.4 Smart Pointers and Memory Management

By their nature object-oriented systems represent and operate on data through a variety of object types, or classes. When a particular class is instantiated to produce an instance of that class, memory allocation occurs so that the instance can store data attribute values and method pointers (i.e., the vtable). This object may then be referenced by other classes or data structures during normal operation of the program. Typically during program execution all references to the instance may disappear at which point the instance must be deleted to recover memory resources. Knowing when to delete an instance, however, is difficult. Deleting the instance too soon results in program crashes; deleting it too late and memory leaks (or excessive memory consumption) will occur. This process of allocating and releasing memory is known as memory management.

In ITK, memory management is implemented through reference counting. This compares to another

popular approach—garbage collection—used by many systems including Java. In reference counting, a count of the number of references to each instance is kept. When the reference goes to zero, the object destroys itself. In garbage collection, a background process sweeps the system identifying instances no longer referenced in the system and deletes them. The problem with garbage collection is that the actual point in time at which memory is deleted is variable. This is unacceptable when an object size may be gigantic (think of a large 3D volume gigabytes in size). Reference counting deletes memory immediately (once all references to an object disappear).

Reference counting is implemented through a `Register()`/`Delete()` member function interface. All instances of an OTB object have a `Register()` method invoked on them by any other object that references an them. The `Register()` method increments the instances' reference count. When the reference to the instance disappears, a `Delete()` method is invoked on the instance that decrements the reference count—this is equivalent to an `UnRegister()` method. When the reference count returns to zero, the instance is destroyed.

This protocol is greatly simplified by using a helper class called a `itk::SmartPointer`. The smart pointer acts like a regular pointer (e.g. supports operators `->` and `*`) but automagically performs a `Register()` when referring to an instance, and an `UnRegister()` when it no longer points to the instance. Unlike most other instances in OTB, SmartPointers can be allocated on the program stack, and are automatically deleted when the scope that the SmartPointer was created is closed. As a result, you should *rarely if ever call Register() or Delete()* in OTB. For example:

```
MyRegistrationFunction()
  { <----- Start of scope

  // here an interpolator is created and associated to the
  // SmartPointer "interp".
  InterpolatorType::Pointer interp = InterpolatorType::New();

  } <------ End of scope
```

In this example, reference counted objects are created (with the `New()` method) with a reference count of one. Assignment to the SmartPointer `interp` does not change the reference count. At the end of scope, `interp` is destroyed, the reference count of the actual interpolator object (referred to by `interp`) is decremented, and if it reaches zero, then the interpolator is also destroyed.

Note that in ITK SmartPointers are always used to refer to instances of classes derived from `itk::LightObject`. Method invocations and function calls often return "real" pointers to instances, but they are immediately assigned to a SmartPointer. Raw pointers are used for non-LightObject classes when the need for speed and/or memory demands a smaller, faster class.

3.2.5 Error Handling and Exceptions

In general, OTB uses exception handling to manage errors during program execution. Exception handling is a standard part of the C++ language and generally takes the form as illustrated below:

```
try
  {
  //...try executing some code here...
  }
catch ( itk::ExceptionObject exp )
  {
  //...if an exception is thrown catch it here
  }
```

where a particular class may throw an exceptions as demonstrated below (this code snippet is taken from `itk::ByteSwapper`:

```
switch ( sizeof(T) )
  {
  //non-error cases go here followed by error case
  default:
    ByteSwapperError e(__FILE__, __LINE__);
    e.SetLocation("SwapBE");
    e.SetDescription("Cannot swap number of bytes requested");
    throw e;
  }
```

Note that `itk::ByteSwapperError` is a subclass of `itk::ExceptionObject`. (In fact in OTB all exceptions should be derived from `itk::ExceptionObject`.) In this example a special constructor and C++ preprocessor variables `__FILE__` and `__LINE__` are used to instantiate the exception object and provide additional information to the user. You can choose to catch a particular exception and hence a specific OTB error, or you can trap *any* OTB exception by catching ExceptionObject.

3.2.6 Event Handling

Event handling in OTB is implemented using the Subject/Observer design pattern [48] (sometimes referred to as the Command/Observer design pattern). In this approach, objects indicate that they are watching for a particular event—invoked by a particular instance–by registering with the instance that they are watching. For example, filters in OTB periodically invoke the `itk::ProgressEvent`. Objects that have registered their interest in this event are notified when the event occurs. The notification occurs via an invocation of a command (i.e., function callback, method invocation, etc.) that is specified during the registration process. (Note that events in OTB are subclasses of EventObject; look in `itkEventObject.h` to determine which events are available.)

To recap via example: various objects in OTB will invoke specific events as they execute (from ProcessObject):

```
this->InvokeEvent( ProgressEvent() );
```

To watch for such an event, registration is required that associates a command (e.g., callback function) with the event: `Object::AddObserver()` method:

```
unsigned long progressTag =
  filter->AddObserver(ProgressEvent(), itk::Command*);
```

When the event occurs, all registered observers are notified via invocation of the associated `Command::Execute()` method. Note that several subclasses of Command are available supporting const and non-const member functions as well as C-style functions. (Look in `Common/Command.h` to find pre-defined subclasses of Command. If nothing suitable is found, derivation is another possibility.)

3.2.7 Multi-Threading

Multithreading is handled in OTB through ITK's high-level design abstraction. This approach provides portable multithreading and hides the complexity of differing thread implementations on the many systems supported by OTB. For example, the class `itk::MultiThreader` provides support for multithreaded execution using `sproc()` on an SGI, or `pthread_create` on any platform supporting POSIX threads.

Multithreading is typically employed by an algorithm during its execution phase. MultiThreader can be used to execute a single method on multiple threads, or to specify a method per thread. For example, in the class `itk::ImageSource` (a superclass for most image processing filters) the `GenerateData()` method uses the following methods:

```
multiThreader->SetNumberOfThreads(int);
multiThreader->SetSingleMethod(ThreadFunctionType, void* data);
multiThreader->SingleMethodExecute();
```

In this example each thread invokes the same method. The multithreaded filter takes care to divide the image into different regions that do not overlap for write operations.

The general philosophy in ITK regarding thread safety is that accessing different instances of a class (and its methods) is a thread-safe operation. Invoking methods on the same instance in different threads is to be avoided.

3.3 Numerics

OTB; as ITK, uses the VNL numerics library to provide resources for numerical programming combining the ease of use of packages like Mathematica and Matlab with the speed of C and the elegance of C++. It provides a C++ interface to the high-quality Fortran routines made available in the public domain by numerical analysis researchers. ITK extends the functionality of VNL by including interface classes between VNL and ITK proper.

The VNL numerics library includes classes for

Matrices and vectors. Standard matrix and vector support and operations on these types.

Specialized matrix and vector classes. Several special matrix and vector class with special numerical properties are available. Class `vnl_diagonal_matrix` provides a fast and convenient diagonal matrix, while fixed size matrices and vectors allow "fast-as-C" computations (see `vnl_matrix_fixed<T,n,m>` and example subclasses `vnl_double_3x3` and `vnl_double_3`).

Matrix decompositions. Classes `vnl_svd<T>`, `vnl_symmetric_eigensystem<T>`, and `vnl_generalized_eigensystem`.

Real polynomials. Class `vnl_real_polynomial` stores the coefficients of a real polynomial, and provides methods of evaluation of the polynomial at any x, while class `vnl_rpoly_roots` provides a root finder.

Optimization. Classes `vnl_levenberg_marquardt`, `vnl_amoeba`, `vnl_conjugate_gradient`, `vnl_lbfgs` allow optimization of user-supplied functions either with or without user-supplied derivatives.

Standardized functions and constants. Class `vnl_math` defines constants (pi, e, eps...) and simple functions (sqr, abs, rnd...). Class `numeric_limits` is from the ISO standard document, and provides a way to access basic limits of a type. For example `numeric_limits<short>::max()` returns the maximum value of a short.

Most VNL routines are implemented as wrappers around the high-quality Fortran routines that have been developed by the numerical analysis community over the last forty years and placed in the public domain. The central repository for these programs is the "netlib" server `http://www.netlib.org/`. The National Institute of Standards and Technology (NIST) provides an excellent search interface to this repository in its *Guide to Available Mathematical Software (GAMS)* at `http://gams.nist.gov`, both as a decision tree and a text search.

ITK also provides additional numerics functionality. A suite of optimizers, that use VNL under the hood and integrate with the registration framework are available. A large collection of statistics functions—not available from VNL—are also provided in the `Insight/Numerics/Statistics` directory. In addition, a complete finite element (FEM) package is available, primarily to support the deformable registration in ITK.

3.4 Data Representation

There are two principal types of data represented in OTB: images and meshes. This functionality is implemented in the classes Image and Mesh, both of which are subclasses of `itk::DataObject`. In OTB, data objects are classes that are meant to be passed around the system and may participate in data flow pipelines (see Section 3.5 on page 34 for more information).

otb::Image represents an *n*-dimensional, regular sampling of data. The sampling direction is parallel to each of the coordinate axes, and the origin of the sampling, inter-pixel spacing, and the number of samples in each direction (i.e., image dimension) can be specified. The sample, or pixel, type in OTB is arbitrary—a template parameter TPixel specifies the type upon template instantiation. (The dimensionality of the image must also be specified when the image class is instantiated.) The key is that the pixel type must support certain operations (for example, addition or difference) if the code is to compile in all cases (for example, to be processed by a particular filter that uses these operations). In practice the OTB user will use a C++ simple type (e.g., int, float) or a pre-defined pixel type and will rarely create a new type of pixel class.

One of the important ITK concepts regarding images is that rectangular, continuous pieces of the image are known as *regions*. Regions are used to specify which part of an image to process, for example in multithreading, or which part to hold in memory. In ITK there are three common types of regions:

1. LargestPossibleRegion—the image in its entirety.
2. BufferedRegion—the portion of the image retained in memory.
3. RequestedRegion—the portion of the region requested by a filter or other class when operating on the image.

The otb::Image class extends the functionalities of the itk::Image in order to take into account particular remote sensing features as geographical projections, etc.

The Mesh class represents an *n*-dimensional, unstructured grid. The topology of the mesh is represented by a set of *cells* defined by a type and connectivity list; the connectivity list in turn refers to points. The geometry of the mesh is defined by the *n*-dimensional points in combination with associated cell interpolation functions. Mesh is designed as an adaptive representational structure that changes depending on the operations performed on it. At a minimum, points and cells are required in order to represent a mesh; but it is possible to add additional topological information. For example, links from the points to the cells that use each point can be added; this provides implicit neighborhood information assuming the implied topology is the desired one. It is also possible to specify boundary cells explicitly, to indicate different connectivity from the implied neighborhood relationships, or to store information on the boundaries of cells.

The mesh is defined in terms of three template parameters: 1) a pixel type associated with the points, cells, and cell boundaries; 2) the dimension of the points (which in turn limits the maximum dimension of the cells); and 3) a "mesh traits" template parameter that specifies the types of the containers and identifiers used to access the points, cells, and/or boundaries. By using the mesh traits carefully, it is possible to create meshes better suited for editing, or those better suited for "read-only" operations, allowing a trade-off between representation flexibility, memory, and speed.

Mesh is a subclass of itk::PointSet. The PointSet class can be used to represent point clouds or randomly distributed landmarks, etc. The PointSet class has no associated topology.

3.5 Data Processing Pipeline

While data objects (e.g., images and meshes) are used to represent data, *process objects* are classes that operate on data objects and may produce new data objects. Process objects are classed as *sources*, *filter objects*, or *mappers*. Sources (such as readers) produce data, filter objects take in data and process it to produce new data, and mappers accept data for output either to a file or some other system. Sometimes the term *filter* is used broadly to refer to all three types.

The data processing pipeline ties together data objects (e.g., images and meshes) and process objects. The pipeline supports an automatic updating mechanism that causes a filter to execute if and only if its input or its internal state changes. Further, the data pipeline supports *streaming*, the ability to automatically break data into smaller pieces, process the pieces one by one, and reassemble the processed data into a final result.

Typically data objects and process objects are connected together using the `SetInput()` and `GetOutput()` methods as follows:

```
typedef otb::Image<float,2> FloatImage2DType;

itk::RandomImageSource<FloatImage2DType>::Pointer random;
random = itk::RandomImageSource<FloatImage2DType>::New();
random->SetMin(0.0);
random->SetMax(1.0);

itk::ShrinkImageFilter<FloatImage2DType,FloatImage2DType>::Pointer shrink;
shrink = itk::ShrinkImageFilter<FloatImage2DType,FloatImage2DType>::New();
shrink->SetInput(random->GetOutput());
shrink->SetShrinkFactors(2);

otb::ImageFileWriter::Pointer<FloatImage2DType> writer;
writer = otb::ImageFileWriter::Pointer<FloatImage2DType>::New();
writer->SetInput (shrink->GetOutput());
writer->SetFileName( ``test.raw'' );
writer->Update();
```

In this example the source object `itk::RandomImageSource` is connected to the `itk::ShrinkImageFilter`, and the shrink filter is connected to the mapper `otb::ImageFileWriter`. When the `Update()` method is invoked on the writer, the data processing pipeline causes each of these filters in order, culminating in writing the final data to a file on disk.

3.6 Spatial Objects

The ITK spatial object framework supports the philosophy that the task of image segmentation and registration is actually the task of object processing. The image is but one medium for representing objects of interest, and much processing and data analysis can and should occur at the object level and not based on the medium used to represent the object.

ITK spatial objects provide a common interface for accessing the physical location and geometric properties of and the relationship between objects in a scene that is independent of the form used to represent those objects. That is, the internal representation maintained by a spatial object may be a list of points internal to an object, the surface mesh of the object, a continuous or parametric representation of the object's internal points or surfaces, and so forth.

The capabilities provided by the spatial objects framework supports their use in object segmentation, registration, surface/volume rendering, and other display and analysis functions. The spatial object framework extends the concept of a "scene graph" that is common to computer rendering packages so as to support these new functions. With the spatial objects framework you can:

1. Specify a spatial object's parent and children objects. In this way, a city may contain roads and those roads can be organized in a tree structure.
2. Query if a physical point is inside an object or (optionally) any of its children.
3. Request the value and derivatives, at a physical point, of an associated intensity function, as specified by an object or (optionally) its children.
4. Specify the coordinate transformation that maps a parent object's coordinate system into a child object's coordinate system.
5. Compute the bounding box of a spatial object and (optionally) its children.
6. Query the resolution at which the object was originally computed. For example, you can query the resolution (i.e., pixel spacing) of the image used to generate a particular instance of a `itk::LineSpatialObject`.

Currently implemented types of spatial objects include: Blob, Ellipse, Group, Image, Line, Surface, and Tube. The `itk::Scene` object is used to hold a list of spatial objects that may in turn have children. Each spatial object can be assigned a color property. Each spatial object type has its own capabilities. For example, `itk::TubeSpatialObject`s indicate to what point on their parent tube they connect.

There are a limited number of spatial objects and their methods in ITK, but their number is growing and their potential is huge. Using the nominal spatial object capabilities, methods such as mutual information registration, can be applied to objects regardless of their internal representation. By having a common API, the same method can be used to register a parametric representation of a building with an image or to register two different segmentations of a particular object in object-based change detection.

Part II

Tutorials

CHAPTER

FOUR

BUILDING SIMPLE APPLICATIONS WITH OTB

Well, that's it, you've just downloaded and installed OTB, lured by the promise that you will be able to do everything with it. That's true, you will be able to do everything but - there is always a *but* - some effort is required.

OTB uses the very powerful systems of generic programing, many classes are already available, some powerful tools are defined to help you with recurrent tasks, but it is not an easy world to enter.

These tutorials are designed to help you enter this world and grasp the logic behind OTB. Each of these tutorials should not take more than 10 minutes (typing included) and each is designed to highlight a specific point. You may not be concerned by the latest tutorials but it is strongly advised to go through the first few which cover the basics you'll use almost everywhere.

4.1 Hello world

Let's start by the typical *Hello world* program. We are going to compile this C++ program linking to your new OTB.

First, create a new folder to put your new programs (all the examples from this tutorial) in and go into this folder.

Since all programs using OTB are handled using the CMake system, we need to create a `CMakeLists.txt` that will be used by CMake to compile our program. An example of this file can be found in the `OTB/Examples/Tutorials` directory. The `CMakeLists.txt` will be very similar between your projects.

Open the `CMakeLists.txt` file and write in the few lines:

```
PROJECT(Tutorials)
```

```
cmake_minimum_required(VERSION 2.6)

FIND_PACKAGE(OTB)
IF(OTB_FOUND)
  INCLUDE(${OTB_USE_FILE})
ELSE(OTB_FOUND)
  MESSAGE(FATAL_ERROR
      "Cannot build OTB project without OTB.  Please set OTB_DIR.")
ENDIF(OTB_FOUND)

ADD_EXECUTABLE(HelloWorldOTB HelloWorldOTB.cxx )
TARGET_LINK_LIBRARIES(HelloWorldOTB OTBCommon OTBIO)
```

The first line defines the name of your project as it appears in Visual Studio (it will have no effect under UNIX or Linux). The second line loads a CMake file with a predefined strategy for finding OTB [1]. If the strategy for finding OTB fails, CMake will prompt you for the directory where OTB is installed in your system. In that case you will write this information in the `OTB_DIR` variable. The line `INCLUDE(${USE_OTB_FILE})` loads the `UseOTB.cmake` file to set all the configuration information from OTB.

The line `ADD_EXECUTABLE` defines as its first argument the name of the executable that will be produced as result of this project. The remaining arguments of `ADD_EXECUTABLE` are the names of the source files to be compiled and linked. Finally, the `TARGET_LINK_LIBRARIES` line specifies which OTB libraries will be linked against this project.

The source code for this example can be found in the file
`Examples/Tutorials/HelloWorldOTB.cxx`.

The following code is an implementation of a small OTB program. It tests including header files and linking with OTB libraries.

```
#include "otbImage.h"
#include <iostream>

int main(int argc, char * argv[])
{
  typedef otb::Image<unsigned short, 2> ImageType;

  ImageType::Pointer image = ImageType::New();

  std::cout << "OTB Hello World !" << std::endl;

  return EXIT_SUCCESS;
}
```

This code instantiates an image whose pixels are represented with type `unsigned short`. The image is then created and assigned to a `itk::SmartPointer`. Later in the text we will discuss

[1] Similar files are provided in CMake for other commonly used libraries, all of them named `Find*.cmake`

SmartPointers in detail, for now think of it as a handle on an instance of an object (see section 3.2.4 for more information).

Once the file is written, run ccmake on the current directory (that is ccmake ./ under Linux/Unix). If OTB is on a non standard place, you will have to tell CMake where it is. Once your done with CMake (you shouldn't have to do it anymore) run make.

You finally have your program. When you run it, you will have the *OTB Hello World !* printed.

Ok, well done! You've just compiled and executed your first OTB program. Actually, using OTB for that is not very useful, and we doubt that you downloaded OTB only to do that. It's time to move on to a more advanced level.

4.2 Pipeline basics: read and write

OTB is designed to read images, process them and write them to disk or view the result. In this tutorial, we are going to see how to read and write images and the basics of the pipeline system.

First, let's add the following lines at the end of the CMakeLists.txt file:

```
ADD_EXECUTABLE(Pipeline Pipeline.cxx )
TARGET_LINK_LIBRARIES(Pipeline OTBCommon OTBIO)
```

Now, create a Pipeline.cxx file.

The source code for this example can be found in the file Examples/Tutorials/Pipeline.cxx.

Start by including some necessary headers and with the usual main declaration:

```
#include "otbImage.h"
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"

int main(int argc, char * argv[])
{
  if (argc != 3)
    {
    std::cerr << "Usage: "
        << argv[0]
        << " <input_filename> <output_filename>"
        << std::endl;
    }
```

Declare the image as an otb::Image, the pixel type is declared as an unsigned char (one byte) and the image is specified as having two dimensions.

```
  typedef otb::Image<unsigned char, 2> ImageType;
```

To read the image, we need an `otb::ImageFileReader` which is templated with the image type.

```
  typedef otb::ImageFileReader<ImageType> ReaderType;
  ReaderType::Pointer reader = ReaderType::New();
```

Then, we need an `otb::ImageFileWriter` also templated with the image type.

```
  typedef otb::ImageFileWriter<ImageType> WriterType;
  WriterType::Pointer writer = WriterType::New();
```

The filenames are passed as arguments to the program. We keep it simple for now and we don't check their validity.

```
  reader->SetFileName(argv[1]);
  writer->SetFileName(argv[2]);
```

Now that we have all the elements, we connect the pipeline, pluging the output of the reader to the input of the writer.

```
  writer->SetInput(reader->GetOutput());
```

And finally, we trigger the pipeline execution calling the Update() method on the last element of the pipeline. The last element will make sure to update all previous elements in the pipeline.

```
  writer->Update();

  return EXIT_SUCCESS;
}
```

Once this file is written you just have to run `make`. The `ccmake` call is not required anymore.

Get one image from the `OTB-Data/Examples` directory from the OTB-Data repository. You can get it either by cloning the OTB data repository (`hg clone http://hg.orfeo-toolbox.org/OTB-Data`), but that might be quite long as this also gets the data to run the tests. Alternatively, you can get it from `http://www.orfeo-toolbox.org/packages/OTB-Data-Examples.tgz`. Take for example get `QB_Suburb.png`.

Now, run your new program as `Pipeline QB_Suburb.png output.png`. You obtain the file `output.png` which is the same image as `QB_Suburb.png`. When you triggered the `Update()` method, OTB opened the original image and wrote it back under another name.

Well... that's nice but a bit complicated for a copy program!

Wait a minute! We didn't specify the file format anywhere! Let's try `Pipeline QB_Suburb.png output.jpg`. And voila! The output image is a jpeg file.

That's starting to be a bit more interesting: this is not just a program to copy image files, but also to convert between image formats.

You have just experienced the pipeline structure which executes the filters only when needed and the automatic image format detection.

Now it's time to do some processing in between.

4.3 Filtering pipeline

We are now going to insert a simple filter to do some processing between the reader and the writer.

Let's first add the 2 following lines to the `CMakeLists.txt` file:

```
ADD_EXECUTABLE(FilteringPipeline FilteringPipeline.cxx )
TARGET_LINK_LIBRARIES(FilteringPipeline OTBCommon OTBIO)
```

The source code for this example can be found in the file `Examples/Tutorials/FilteringPipeline.cxx`.

We are going to use the `itk::GradientMagnitudeImageFilter` to compute the gradient of the image. The begining of the file is similar to the Pipeline.cxx.

We include the required headers, without forgetting to add the header for the `itk::GradientMagnitudeImageFilter`.

```
#include "otbImage.h"
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
#include "itkGradientMagnitudeImageFilter.h"

int main(int argc, char * argv[])
{
  if (argc != 3)
    {
    std::cerr << "Usage: "
        << argv[0]
        << " <input_filename> <output_filename>"
        << std::endl;
    }
```

We declare the image type, the reader and the writer as before:

```
  typedef otb::Image<unsigned char, 2> ImageType;

  typedef otb::ImageFileReader<ImageType> ReaderType;
  ReaderType::Pointer reader = ReaderType::New();

  typedef otb::ImageFileWriter<ImageType> WriterType;
  WriterType::Pointer writer = WriterType::New();

  reader->SetFileName(argv[1]);
  writer->SetFileName(argv[2]);
```

Now we have to declare the filter. It is templated with the input image type and the output image type like many filters in OTB. Here we are using the same type for the input and the output images:

```
  typedef itk::GradientMagnitudeImageFilter
  <ImageType, ImageType> FilterType;
  FilterType::Pointer filter = FilterType::New();
```

Let's plug the pipeline:

```
  filter->SetInput(reader->GetOutput());
  writer->SetInput(filter->GetOutput());
```

And finally, we trigger the pipeline execution calling the `Update()` method on the writer

```
  writer->Update();

  return EXIT_SUCCESS;
}
```

Compile with `make` and execute as `FilteringPipeline QB_Suburb.png output.png`.

You have the filtered version of your image in the `output.png` file.

Now, you can practice a bit and try to replace the filter by one of the 150+ filters which inherit from the `otb::ImageToImageFilter` class. You will definitely find some useful filters here!

4.4 Handling types: scaling output

If you tried some other filter in the previous example, you may have noticed that in some cases, it does not make sense to save the output directly as an integer. This is the case if you tried the `itk::CannyEdgeDetectionImageFilter`. If you tried to use it directly in the previous example, you will have some warning about converting to unsigned char from double.

The output of the Canny edge detection is a floating point number. A simple solution would be to used double as the pixel type. Unfortunately, most image formats use integer typed and you should convert the result to an integer image if you still want to visualize your images with your usual viewer (we will see in a tutorial later how you can avoid that using the built-in viewer).

To realize this conversion, we will use the `itk::RescaleIntensityImageFilter`.

Add the two lines to the `CMakeLists.txt` file:

```
ADD_EXECUTABLE(ScalingPipeline ScalingPipeline.cxx )
TARGET_LINK_LIBRARIES(ScalingPipeline OTBCommon OTBIO)
```

The source code for this example can be found in the file
`Examples/Tutorials/ScalingPipeline.cxx`.

This example illustrates the use of the `itk::RescaleIntensityImageFilter` to convert the result for proper display.

We include the required header including the header for the `itk::CannyEdgeImageFilter` and the `itk::RescaleIntensityImageFilter`.

```
#include "otbImage.h"
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
#include "itkCannyEdgeDetectionImageFilter.h"
#include "itkRescaleIntensityImageFilter.h"

int main(int argc, char * argv[])
{
  if (argc != 3)
    {
    std::cerr << "Usage: "
        << argv[0]
        << " <input_filename> <output_filename>"
        << std::endl;
    }
```

We need to declare two different image types, one for the internal processing and one to output the results:

```
  typedef double                    PixelType;
  typedef otb::Image<PixelType, 2>  ImageType;

  typedef unsigned char                    OutputPixelType;
  typedef otb::Image<OutputPixelType, 2>  OutputImageType;
```

We declare the reader with the image template using the pixel type double. It is worth noticing that this instanciation does not imply anything about the type of the input image. The original image can be anything, the reader will just convert the result to double.

The writer is templated with the unsigned char image to be able to save the result on one byte images (like png for example).

```
  typedef otb::ImageFileReader<ImageType> ReaderType;
  ReaderType::Pointer reader = ReaderType::New();

  typedef otb::ImageFileWriter<OutputImageType> WriterType;
  WriterType::Pointer writer = WriterType::New();

  reader->SetFileName(argv[1]);
  writer->SetFileName(argv[2]);
```

Now we are declaring the edge detection filter which is going to work with double input and output.

```
  typedef itk::CannyEdgeDetectionImageFilter
  <ImageType, ImageType> FilterType;
  FilterType::Pointer filter = FilterType::New();
```

Here comes the interesting part: we declare the `itk::RescaleIntensityImageFilter`. The input image type is the output type of the edge detection filter. The output type is the same as the input type of the writer.

Desired minimum and maximum values for the output are specified by the methods `SetOutputMinimum()` and `SetOutputMaximum()`.

This filter will actually rescale all the pixels of the image but also cast the type of these pixels.

```
  typedef itk::RescaleIntensityImageFilter
  <ImageType, OutputImageType> RescalerType;
  RescalerType::Pointer rescaler = RescalerType::New();

  rescaler->SetOutputMinimum(0);
  rescaler->SetOutputMaximum(255);
```

Let's plug the pipeline:

```
  filter->SetInput(reader->GetOutput());
  rescaler->SetInput(filter->GetOutput());
  writer->SetInput(rescaler->GetOutput());
```

And finally, we trigger the pipeline execution calling the Update() method on the writer

```
  writer->Update();

  return EXIT_SUCCESS;
}
```

As you should be getting used to it by now, compile with `make` and execute as `ScalingPipeline QB_Suburb.png output.png`.

You have the filtered version of your image in the `output.png` file.

4.5 Working with multispectral or color images

So far, as you may have noticed, we have been working with grey level images, i.e. with only one spectral band. If you tried to process a color image with some of the previous examples you have probably obtained a deceiving grey result.

Often, satellite images combine several spectral band to help the identification of materials: this is called multispectral imagery. In this tutorial, we are going to explore some of the mechanisms used by OTB to process multispectral images.

Add the following lines in the `CMakeLists.txt` file:

```
ADD_EXECUTABLE(Multispectral Multispectral.cxx )
TARGET_LINK_LIBRARIES(Multispectral OTBCommon OTBIO)
```

The source code for this example can be found in the file
`Examples/Tutorials/Multispectral.cxx`.

First, we are going to use `otb::VectorImage` instead of the now traditionnal `otb::Image`. So we include the required header:

```
#include "otbVectorImage.h"
```

We also include some other header which will be useful later. Note that we are still using the `otb::Image` in this example for some of the output.

```
#include "otbImage.h"
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
#include "otbMultiToMonoChannelExtractROI.h"
#include "itkShiftScaleImageFilter.h"
#include "otbPerBandVectorImageFilter.h"

int main(int argc, char * argv[])
{
  if (argc != 4)
    {
    std::cerr << "Usage: "
        << argv[0]
        << " <input_filename> <output_extract> <output_shifted_scaled>"
        << std::endl;
    }
```

We want to read a multispectral image so we declare the image type and the reader. As we have done in the previous example we get the filename from the command line.

```
  typedef unsigned short int              PixelType;
  typedef otb::VectorImage<PixelType, 2> VectorImageType;

  typedef otb::ImageFileReader<VectorImageType> ReaderType;
  ReaderType::Pointer reader = ReaderType::New();

  reader->SetFileName(argv[1]);
```

Sometime, you need to process only one spectral band of the image. To get only one of the spectral band we use the /doxygenotbMultiToMonoChannelExtractROI. The declaration is as usual:

```
  typedef otb::MultiToMonoChannelExtractROI<PixelType, PixelType>
  ExtractChannelType;
  ExtractChannelType::Pointer extractChannel = ExtractChannelType::New();
```

We need to pass the parameters to the filter for the extraction. This filter also allow to extract only a spatial subset of the image. However, we will extract the whole channel in this case.

To do that, we need to pass the desired region using the `SetExtractionRegion()` (method such as `SetStartX`, `SetSizeX` are also available). We get the region from the reader with the

`GetLargestPossibleRegion()` method. Before doing that we need to read the metadata from the file: this is done by calling the `UpdateOutputInformation()` on the reader's output. The difference with the `Update()` is that the pixel array is not allocated (yet !) and reduce the memory usage.

```
reader->UpdateOutputInformation();
extractChannel->SetExtractionRegion(
  reader->GetOutput()->GetLargestPossibleRegion());
```

We chose the channel number to extract (starting from 1) and we plug the pipeline.

```
extractChannel->SetChannel(3);
extractChannel->SetInput(reader->GetOutput());
```

To output this image, we need a writer. As the output of the `otb::MultiToMonoChannelExtractROI` is a `otb::Image`, we need to template the writer with this type.

```
typedef otb::Image<PixelType, 2>                ImageType;
typedef otb::ImageFileWriter<ImageType> WriterType;
WriterType::Pointer writer = WriterType::New();

writer->SetFileName(argv[2]);
writer->SetInput(extractChannel->GetOutput());

writer->Update();
```

After this, we have a one band image that we can process with most OTB filters.

In some situation, you may want to apply the same process to all bands of the image. You don't have to extract each band and process them separately. There is several situations:

- the filter (or the combination of filters) you want to use are doing operations that are well defined for `itk::VariableLengthVector` (which is the pixel type), then you don't have to do anything special.
- if this is not working, you can look for the equivalent filter specially designed for vector images.
- some of the filter you need to use applies operations undefined for `itk::VariableLengthVector`, then you can use the `otb::PerBandVectorImageFilter` specially designed for this purpose.

Let's see how this filter is working. We chose to apply the `itk::ShiftScaleImageFilter` to each of the spectral band. We start by declaring the filter on a normal `otb::Image`. Note that we don't need to specify any input for this filter.

```
  typedef itk::ShiftScaleImageFilter<ImageType, ImageType> ShiftScaleType;
  ShiftScaleType::Pointer shiftScale = ShiftScaleType::New();
  shiftScale->SetScale(0.5);
  shiftScale->SetShift(10);
```

We declare the `otb::PerBandVectorImageFilter` which has three template: the input image type, the output image type and the filter type to apply to each band.

The filter is selected using the `SetFilter()` method and the input by the usual `SetInput()` method.

```
  typedef otb::PerBandVectorImageFilter
  <VectorImageType, VectorImageType, ShiftScaleType> VectorFilterType;
  VectorFilterType::Pointer vectorFilter = VectorFilterType::New();
  vectorFilter->SetFilter(shiftScale);

  vectorFilter->SetInput(reader->GetOutput());
```

Now, we just have to save the image using a writer templated over an `otb::VectorImage`:

```
  typedef otb::ImageFileWriter<VectorImageType> VectorWriterType;
  VectorWriterType::Pointer writerVector = VectorWriterType::New();

  writerVector->SetFileName(argv[3]);
  writerVector->SetInput(vectorFilter->GetOutput());

  writerVector->Update();

  return EXIT_SUCCESS;
}
```

Compile with `make` and execute as `./Multispectral qb_RoadExtract.tif qb_blue.tif qb_shiftscale.tif`.

4.6 Parsing command line arguments

Well, if you play with some other filters in the previous example, you probably noticed that in many cases, you need to set some parameters to the filters. Ideally, you want to set some of these parameters from the command line.

In OTB, there is a mechanism to help you parse the command line parameters. Let try it!

Add the following lines in the `CMakeLists.txt` file:

```
ADD_EXECUTABLE(SmarterFilteringPipeline SmarterFilteringPipeline.cxx )
TARGET_LINK_LIBRARIES(SmarterFilteringPipeline OTBCommon OTBIO)
```

The source code for this example can be found in the file `Examples/Tutorials/SmarterFilteringPipeline.cxx`.

We are going to use the `otb::HarrisImageFilter` to find the points of interest in one image.

The derivative computation is performed by a convolution with the derivative of a Gaussian kernel of variance σ_D (derivation scale) and the smoothing of the image is performed by convolving with a Gaussian kernel of variance σ_I (integration scale). This allows the computation of the following matrix:

$$\mu(\mathbf{x},\sigma_I,\sigma_D) = \sigma_D^2 g(\sigma_I) \star \begin{bmatrix} L_x^2(\mathbf{x},\sigma_D) & L_x L_y^2(\mathbf{x},\sigma_D) \\ L_x L_y^2(\mathbf{x},\sigma_D) & L_y^2(\mathbf{x},\sigma_D) \end{bmatrix}$$

The output of the detector is $\det(\mu) - \alpha \mathrm{trace}^2(\mu)$.

We want to set 3 parameters of this filter through the command line: σ_D (SigmaD), σ_I (SigmaI) and α (Alpha).

We are also going to do the things properly and catch the exceptions.

Let first add the two following headers:

```
#include "itkMacro.h"
#include "otbCommandLineArgumentParser.h"
```

The first one is to handle the exceptions, the second one to help us parse the command line.

We include the other required headers, without forgetting to add the header for the `otb::HarrisImageFilter`. Then we start the usual main function.

```
#include "otbImage.h"
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
#include "itkRescaleIntensityImageFilter.h"
#include "otbHarrisImageFilter.h"

int main(int argc, char * argv[])
{
```

To handle the exceptions properly, we need to put all the instructions inside a `try`.

```
  try
    {
```

Now, we can declare the `otb::CommandLineArgumentParser` which is going to parse the command line, select the proper variables, handle the missing compulsory arguments and print an error message if necessary.

Let's declare the parser:

```
    typedef otb::CommandLineArgumentParser ParserType;
    ParserType::Pointer parser = ParserType::New();
```

It's now time to tell the parser what are the options we want. Special options are available for input and output images with the `AddInputImage()` and `AddOutputImage()` methods.

For the other options, we need to use the `AddOption()` method. This method allows us to specify

- the name of the option
- a message to explain the meaning of this option
- a shortcut for this option
- the number of expected parameters for this option
- whether or not this option is compulsory

```
parser->SetProgramDescription(
  "This program applies a Harris detector on the input image");
parser->AddInputImage();
parser->AddOutputImage();
parser->AddOption("--SigmaD",
                  "Set the sigmaD parameter. Default is 1.0.",
                  "-d",
                  1,
                  false);
parser->AddOption("--SigmaI",
                  "Set the sigmaI parameter. Default is 1.0.",
                  "-i",
                  1,
                  false);
parser->AddOption("--Alpha",
                  "Set the alpha parameter. Default is 1.0.",
                  "-a",
                  1,
                  false);
```

Now that the parser has all this information, it can actually look at the command line to parse it. We have to do this within a `try` - `catch` loop to handle exceptions nicely.

```
typedef otb::CommandLineArgumentParseResult ParserResultType;
ParserResultType::Pointer parseResult = ParserResultType::New();

try
  {
  parser->ParseCommandLine(argc, argv, parseResult);
  }

catch (itk::ExceptionObject& err)
  {
  std::string descriptionException = err.GetDescription();
  if (descriptionException.find("ParseCommandLine(): Help Parser")
      != std::string::npos)
    {
```

```
    return EXIT_SUCCESS;
    }
  if (descriptionException.find("ParseCommandLine(): Version Parser")
      != std::string::npos)
    {
    return EXIT_SUCCESS;
    }
  return EXIT_FAILURE;
  }
```

Now, we can declare the image type, the reader and the writer as before:

```
typedef double                    PixelType;
typedef otb::Image<PixelType, 2> ImageType;

typedef unsigned char                   OutputPixelType;
typedef otb::Image<OutputPixelType, 2> OutputImageType;

typedef otb::ImageFileReader<ImageType> ReaderType;
ReaderType::Pointer reader = ReaderType::New();

typedef otb::ImageFileWriter<OutputImageType> WriterType;
WriterType::Pointer writer = WriterType::New();
```

We are getting the filenames for the input and the output images directly from the parser:

```
reader->SetFileName(parseResult->GetInputImage().c_str());
writer->SetFileName(parseResult->GetOutputImage().c_str());
```

Now we have to declare the filter. It is templated with the input image type and the output image type like many filters in OTB. Here we are using the same type for the input and the output images:

```
typedef otb::HarrisImageFilter
<ImageType, ImageType> FilterType;
FilterType::Pointer filter = FilterType::New();
```

We set the filter parameters from the parser. The method `IsOptionPresent()` let us know if an optional option was provided in the command line.

```
if (parseResult->IsOptionPresent("--SigmaD"))
  filter->SetSigmaD(
    parseResult->GetParameterDouble("--SigmaD"));

if (parseResult->IsOptionPresent("--SigmaI"))
  filter->SetSigmaI(
    parseResult->GetParameterDouble("--SigmaI"));

if (parseResult->IsOptionPresent("--Alpha"))
  filter->SetAlpha(
    parseResult->GetParameterDouble("--Alpha"));
```

We add the rescaler filter as before

```
    typedef itk::RescaleIntensityImageFilter
    <ImageType, OutputImageType> RescalerType;
    RescalerType::Pointer rescaler = RescalerType::New();

    rescaler->SetOutputMinimum(0);
    rescaler->SetOutputMaximum(255);
```

Let's plug the pipeline:

```
    filter->SetInput(reader->GetOutput());
    rescaler->SetInput(filter->GetOutput());
    writer->SetInput(rescaler->GetOutput());
```

We trigger the pipeline execution calling the `Update()` method on the writer

```
    writer->Update();

    }
```

Finally, we have to handle exceptions we may have raised before

```
  catch (itk::ExceptionObject& err)
    {
    std::cout << "Following otbException catch :" << std::endl;
    std::cout << err << std::endl;
    return EXIT_FAILURE;
    }
  catch (std::bad_alloc& err)
    {
    std::cout << "Exception bad_alloc : " << (char*) err.what() << std::endl;
    return EXIT_FAILURE;
    }
  catch (...)
    {
    std::cout << "Unknown Exception found !" << std::endl;
    return EXIT_FAILURE;
    }
  return EXIT_SUCCESS;
}
```

Compile with `make` as usual. The execution is a bit different now as we have an automatic parsing of the command line. First, try to execute as `SmarterFilteringPipeline` without any argument.

The usage message (automatically generated) appears:

```
'--InputImage' option is obligatory !!!

 Usage : ./SmarterFilteringPipeline
      [--help|-h]           :  Help
      [--version|-v]        :  Version
```

```
       --InputImage|-in     :  input image file name   (1 parameter)
       --OutputImage|-out   :  output image file name   (1 parameter)
      [--SigmaD|-d]         :  Set the sigmaD parameter of the Harris points of
interest  algorithm. Default is 1.0.  (1 parameter)
      [--SigmaI|-i]         :  Set the SigmaI parameter of the Harris points of
interest  algorithm. Default is 1.0.  (1 parameter)
      [--Alpha|-a]          :  Set the alpha parameter of the Harris points of
interest  algorithm. Default is 1.0.  (1 parameter)
```

That looks a bit more professional: another user should be able to play with your program. As this is automatic, that's a good way not to forget to document your programs.

So now you have a better idea of the command line options that are possible. Try `SmarterFilteringPipeline -in QB_Suburb.png -out output.png` for a basic version with the default values.

If you want a result that looks a bit better, you have to adjust the parameter with `SmarterFilteringPipeline -in QB_Suburb.png -out output.png -d 1.5 -i 2 -a 0.1` for example.

4.7 Going from raw satellite images to useful products

Quite often, when you buy satellite images, you end up with several images. In the case of optical satellite, you often have a panchromatic spectral band with the highest spatial resolution and a multispectral product of the same area with a lower resolution. The resolution ratio is likely to be around 4.

To get the best of the image processing algorithms, you want to combine these data to produce a new image with the highest spatial resolution and several spectral band. This step is called fusion and you can find more details about it in 13. However, the fusion suppose that your two images represents exactly the same area. There are different solutions to process your data to reach this situation. Here we are going to use the metadata available with the images to produce an orthorectification as detailled in 11.

First you need to add the following lines in the `CMakeLists.txt` file:

```
ADD_EXECUTABLE(OrthoFusion  OrthoFusion.cxx)
TARGET_LINK_LIBRARIES(OrthoFusion OTBProjections OTBCommon OTBIO)
```

The source code for this example can be found in the file
`Examples/Tutorials/OrthoFusion.cxx`.

Start by including some necessary headers and with the usual `main` declaration. Apart from the classical header related to image input and output. We need the headers related to the fusion and the

orthorectification. One header is also required to be able to process vector images (the XS one) with the orthorectification.

```
#include "otbImage.h"
#include "otbVectorImage.h"
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"

#include "otbOrthoRectificationFilter.h"
#include "otbGenericMapProjection.h"

#include "otbSimpleRcsPanSharpeningFusionImageFilter.h"
#include "otbStandardFilterWatcher.h"

int main(int argc, char* argv[])
{
```

We initialize ossim which is required for the orthorectification and we check that all parameters are provided. Basically, we need:

- the name of the input PAN image;
- the name of the input XS image;
- the desired name for the output;
- as the coordinates are given in UTM, we need the UTM zone number;
- of course, we need the UTM coordinates of the final image;
- the size in pixels of the final image;
- and the sampling of the final image.

We check that all those parameters are provided.

```
  if (argc != 12)
    {
    std::cout << argv[0] << " <input_pan_filename> <input_xs_filename> ";
    std::cout << "<output_filename> <utm zone> <hemisphere N/S>  ";
    std::cout << "<x_ground_upper_left_corner> <y_ground_upper_left_corner> ";
    std::cout << "<x_Size> <y_Size> ";
    std::cout << "<x_groundSamplingDistance> ";
    std::cout << "<y_groundSamplingDistance "
              << "(negative since origin is upper left)>"
              << std::endl;

    return EXIT_FAILURE;
    }
```

We declare the different images, readers and writer:

```
typedef otb::Image<unsigned int, 2>                    ImageType;
typedef otb::VectorImage<unsigned int, 2>              VectorImageType;
typedef otb::Image<double, 2>                          DoubleImageType;
typedef otb::VectorImage<double, 2>                    DoubleVectorImageType;
typedef otb::ImageFileReader<ImageType>                ReaderType;
typedef otb::ImageFileReader<VectorImageType>          VectorReaderType;
typedef otb::ImageFileWriter<VectorImageType> WriterType;

ReaderType::Pointer       readerPAN = ReaderType::New();
VectorReaderType::Pointer readerXS = VectorReaderType::New();
WriterType::Pointer       writer = WriterType::New();

readerPAN->SetFileName(argv[1]);
readerXS->SetFileName(argv[2]);
writer->SetFileName(argv[3]);
```

We declare the projection (here we chose the UTM projection, other choices are possible) and retrieve the paremeters from the command line:

- the UTM zone
- the hemisphere

```
typedef otb::GenericMapProjection<otb::TransformDirection::INVERSE> InverseProjectionType;
InverseProjectionType::Pointer utmMapProjection = InverseProjectionType::New();
utmMapProjection->SetWkt("Utm");
utmMapProjection->SetParameter("Zone", argv[4]);
utmMapProjection->SetParameter("Hemisphere", argv[5]);
```

We will need to pass several parameters to the orthorectification concerning the desired output region:

```
ImageType::IndexType start;
start[0] = 0;
start[1] = 0;

ImageType::SizeType size;
size[0] = atoi(argv[8]);
size[1] = atoi(argv[9]);

ImageType::SpacingType spacing;
spacing[0] = atof(argv[10]);
spacing[1] = atof(argv[11]);

ImageType::PointType origin;
origin[0] = strtod(argv[6], NULL);
origin[1] = strtod(argv[7], NULL);
```

We declare the orthorectification filter. And provide the different parameters:

```
typedef otb::OrthoRectificationFilter<ImageType, DoubleImageType,
    InverseProjectionType>
OrthoRectifFilterType;

OrthoRectifFilterType::Pointer orthoRectifPAN =
  OrthoRectifFilterType::New();
orthoRectifPAN->SetMapProjection(utmMapProjection);

orthoRectifPAN->SetInput(readerPAN->GetOutput());

orthoRectifPAN->SetOutputStartIndex(start);
orthoRectifPAN->SetOutputSize(size);
orthoRectifPAN->SetOutputSpacing(spacing);
orthoRectifPAN->SetOutputOrigin(origin);
```

Now we are able to have the orthorectified area from the PAN image. We just have to follow a similar process for the XS image.

```
typedef otb::OrthoRectificationFilter<VectorImageType,
    DoubleVectorImageType, InverseProjectionType>
VectorOrthoRectifFilterType;


VectorOrthoRectifFilterType::Pointer orthoRectifXS =
  VectorOrthoRectifFilterType::New();

orthoRectifXS->SetMapProjection(utmMapProjection);

orthoRectifXS->SetInput(readerXS->GetOutput());

orthoRectifXS->SetOutputStartIndex(start);
orthoRectifXS->SetOutputSize(size);
orthoRectifXS->SetOutputSpacing(spacing);
orthoRectifXS->SetOutputOrigin(origin);
```

It's time to declare the fusion filter and set its inputs:

```
typedef otb::SimpleRcsPanSharpeningFusionImageFilter
<DoubleImageType, DoubleVectorImageType, VectorImageType> FusionFilterType;
FusionFilterType::Pointer fusion = FusionFilterType::New();
fusion->SetPanInput(orthoRectifPAN->GetOutput());
fusion->SetXsInput(orthoRectifXS->GetOutput());
```

And we can plug it to the writer. To be able to process the images by tiles, we use the `SetAutomaticTiledStreaming()` method of the writer. We trigger the pipeline execution with the `Update()` method.

```
writer->SetInput(fusion->GetOutput());

writer->SetAutomaticTiledStreaming();

otb::StandardFilterWatcher watcher(writer, "OrthoFusion");
```

```
  writer->Update();

  return EXIT_SUCCESS;

}
```

Part III

User's guide

CHAPTER

FIVE

DATA REPRESENTATION

This chapter introduces the basic classes responsible for representing data in OTB. The most common classes are the `otb::Image`, the `itk::Mesh` and the `itk::PointSet`.

5.1 Image

The `otb::Image` class follows the spirit of Generic Programming, where types are separated from the algorithmic behavior of the class. OTB supports images with any pixel type and any spatial dimension.

5.1.1 Creating an Image

The source code for this example can be found in the file
`Examples/DataRepresentation/Image/Image1.cxx`.

This example illustrates how to manually construct an `otb::Image` class. The following is the minimal code needed to instantiate, declare and create the image class.

First, the header file of the Image class must be included.

```
#include "otbImage.h"
```

Then we must decide with what type to represent the pixels and what the dimension of the image will be. With these two parameters we can instantiate the image class. Here we create a 2D image, which is what we often use in remote sensing applications, anyway, with `unsigned short` pixel data.

```
typedef otb::Image<unsigned short, 2> ImageType;
```

The image can then be created by invoking the `New()` operator from the corresponding image type and assigning the result to a `itk::SmartPointer`.

```
ImageType::Pointer image = ImageType::New();
```

In OTB, images exist in combination with one or more *regions*. A region is a subset of the image and indicates a portion of the image that may be processed by other classes in the system. One of the most common regions is the *LargestPossibleRegion*, which defines the image in its entirety. Other important regions found in OTB are the *BufferedRegion*, which is the portion of the image actually maintained in memory, and the *RequestedRegion*, which is the region requested by a filter or other class when operating on the image.

In OTB, manually creating an image requires that the image is instantiated as previously shown, and that regions describing the image are then associated with it.

A region is defined by two classes: the `itk::Index` and `itk::Size` classes. The origin of the region within the image with which it is associated is defined by Index. The extent, or size, of the region is defined by Size. Index is represented by a n-dimensional array where each component is an integer indicating—in topological image coordinates—the initial pixel of the image. When an image is created manually, the user is responsible for defining the image size and the index at which the image grid starts. These two parameters make it possible to process selected regions.

The starting point of the image is defined by an Index class that is an n-dimensional array where each component is an integer indicating the grid coordinates of the initial pixel of the image.

```
ImageType::IndexType start;

start[0] =   0;  // first index on X
start[1] =   0;  // first index on Y
```

The region size is represented by an array of the same dimension of the image (using the Size class). The components of the array are unsigned integers indicating the extent in pixels of the image along every dimension.

```
ImageType::SizeType size;

size[0]  = 200;  // size along X
size[1]  = 200;  // size along Y
```

Having defined the starting index and the image size, these two parameters are used to create an ImageRegion object which basically encapsulates both concepts. The region is initialized with the starting index and size of the image.

```
ImageType::RegionType region;

region.SetSize(size);
region.SetIndex(start);
```

Finally, the region is passed to the `Image` object in order to define its extent and origin. The `SetRegions` method sets the LargestPossibleRegion, BufferedRegion, and RequestedRegion simultaneously. Note that none of the operations performed to this point have allocated memory for the

image pixel data. It is necessary to invoke the `Allocate()` method to do this. Allocate does not require any arguments since all the information needed for memory allocation has already been provided by the region.

```
image->SetRegions(region);
image->Allocate();
```

In practice it is rare to allocate and initialize an image directly. Images are typically read from a source, such a file or data acquisition hardware. The following example illustrates how an image can be read from a file.

5.1.2 Reading an Image from a File

The source code for this example can be found in the file
`Examples/DataRepresentation/Image/Image2.cxx`.

The first thing required to read an image from a file is to include the header file of the `otb::ImageFileReader` class.

```
#include "otbImageFileReader.h"
```

Then, the image type should be defined by specifying the type used to represent pixels and the dimensions of the image.

```
typedef unsigned char PixelType;
const unsigned int Dimension = 2;

typedef otb::Image<PixelType, Dimension> ImageType;
```

Using the image type, it is now possible to instantiate the image reader class. The image type is used as a template parameter to define how the data will be represented once it is loaded into memory. This type does not have to correspond exactly to the type stored in the file. However, a conversion based on C-style type casting is used, so the type chosen to represent the data on disk must be sufficient to characterize it accurately. Readers do not apply any transformation to the pixel data other than casting from the pixel type of the file to the pixel type of the ImageFileReader. The following illustrates a typical instantiation of the ImageFileReader type.

```
typedef otb::ImageFileReader<ImageType> ReaderType;
```

The reader type can now be used to create one reader object. A `itk::SmartPointer` (defined by the `::Pointer` notation) is used to receive the reference to the newly created reader. The `New()` method is invoked to create an instance of the image reader.

```
ReaderType::Pointer reader = ReaderType::New();
```

The minimum information required by the reader is the filename of the image to be loaded in memory. This is provided through the `SetFileName()` method. The file format here is inferred from

the filename extension. The user may also explicitly specify the data format explicitly using the `itk::ImageIO` (See Chapter 6.1 97 for more information):

```
const char * filename = argv[1];
reader->SetFileName(filename);
```

Reader objects are referred to as pipeline source objects; they respond to pipeline update requests and initiate the data flow in the pipeline. The pipeline update mechanism ensures that the reader only executes when a data request is made to the reader and the reader has not read any data. In the current example we explicitly invoke the `Update()` method because the output of the reader is not connected to other filters. In normal application the reader's output is connected to the input of an image filter and the update invocation on the filter triggers an update of the reader. The following line illustrates how an explicit update is invoked on the reader.

```
reader->Update();
```

Access to the newly read image can be gained by calling the `GetOutput()` method on the reader. This method can also be called before the update request is sent to the reader. The reference to the image will be valid even though the image will be empty until the reader actually executes.

```
ImageType::Pointer image = reader->GetOutput();
```

Any attempt to access image data before the reader executes will yield an image with no pixel data. It is likely that a program crash will result since the image will not have been properly initialized.

5.1.3 Accessing Pixel Data

The source code for this example can be found in the file
`Examples/DataRepresentation/Image/Image3.cxx`.

This example illustrates the use of the `SetPixel()` and `GetPixel()` methods. These two methods provide direct access to the pixel data contained in the image. Note that these two methods are relatively slow and should not be used in situations where high-performance access is required. Image iterators are the appropriate mechanism to efficiently access image pixel data.

The individual position of a pixel inside the image is identified by a unique index. An index is an array of integers that defines the position of the pixel along each coordinate dimension of the image. The IndexType is automatically defined by the image and can be accessed using the scope operator like `itk::Index`. The length of the array will match the dimensions of the associated image.

The following code illustrates the declaration of an index variable and the assignment of values to each of its components. Please note that `Index` does not use SmartPointers to access it. This is because `Index` is a light-weight object that is not intended to be shared between objects. It is more efficient to produce multiple copies of these small objects than to share them using the SmartPointer mechanism.

The following lines declare an instance of the index type and initialize its content in order to associate it with a pixel position in the image.

```
ImageType::IndexType pixelIndex;

pixelIndex[0] = 27;   // x position
pixelIndex[1] = 29;   // y position
```

Having defined a pixel position with an index, it is then possible to access the content of the pixel in the image. The `GetPixel()` method allows us to get the value of the pixels.

```
ImageType::PixelType pixelValue = image->GetPixel(pixelIndex);
```

The `SetPixel()` method allows us to set the value of the pixel.

```
image->SetPixel(pixelIndex,   pixelValue + 1);
```

Please note that `GetPixel()` returns the pixel value using copy and not reference semantics. Hence, the method cannot be used to modify image data values.

Remember that both `SetPixel()` and `GetPixel()` are inefficient and should only be used for debugging or for supporting interactions like querying pixel values by clicking with the mouse.

5.1.4 Defining Origin and Spacing

The source code for this example can be found in the file
`Examples/DataRepresentation/Image/Image4.cxx`.

Even though OTB can be used to perform general image processing tasks, the primary purpose of the toolkit is the processing of remote sensing image data. In that respect, additional information about the images is considered mandatory. In particular the information associated with the physical spacing between pixels and the position of the image in space with respect to some world coordinate system are extremely important.

Image origin and spacing are fundamental to many applications. Registration, for example, is performed in physical coordinates. Improperly defined spacing and origins will result in inconsistent results in such processes. Remote sensing images with no spatial information should not be used for image analysis, feature extraction, GIS input, etc. In other words, remote sensing images lacking spatial information are not only useless but also hazardous.

Figure 5.1 illustrates the main geometrical concepts associated with the `otb::Image`. In this figure, circles are used to represent the center of pixels. The value of the pixel is assumed to exist as a Dirac Delta Function located at the pixel center. Pixel spacing is measured between the pixel centers and can be different along each dimension. The image origin is associated with the coordinates of the first pixel in the image. A *pixel* is considered to be the rectangular region surrounding the pixel center holding the data value. This can be viewed as the Voronoi region of the image grid, as

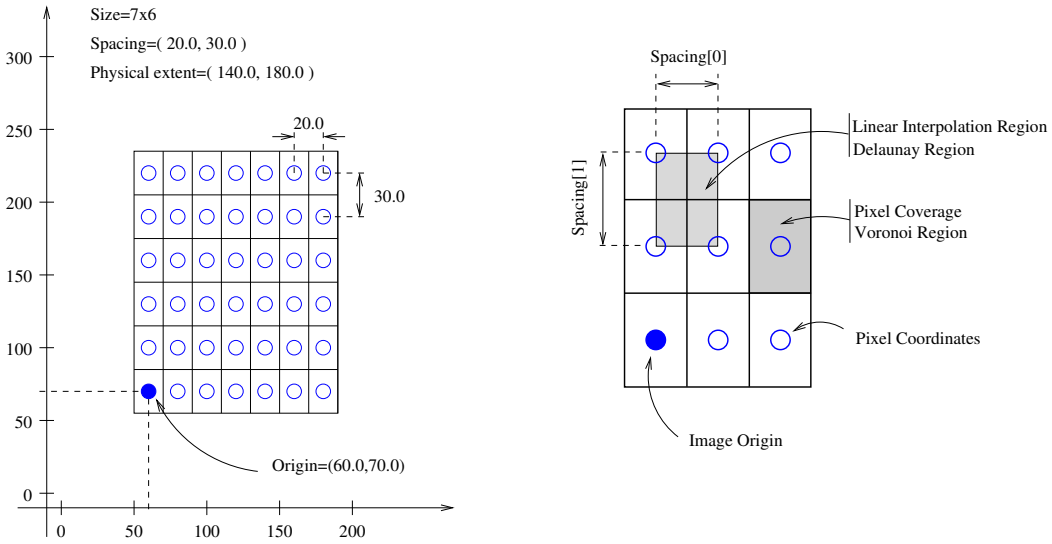


Figure 5.1: Geometrical concepts associated with the OTB image.

illustrated in the right side of the figure. Linear interpolation of image values is performed inside the Delaunay region whose corners are pixel centers.

Image spacing is represented in a `FixedArray` whose size matches the dimension of the image. In order to manually set the spacing of the image, an array of the corresponding type must be created. The elements of the array should then be initialized with the spacing between the centers of adjacent pixels. The following code illustrates the methods available in the Image class for dealing with spacing and origin.

```
ImageType::SpacingType spacing;

// Note: measurement units (e.g., meters, feet, etc.) are defined by the application.
spacing[0] = 0.70; // spacing along X
spacing[1] = 0.70; // spacing along Y
```

The array can be assigned to the image using the `SetSpacing()` method.

```
image->SetSpacing(spacing);
```

The spacing information can be retrieved from an image by using the `GetSpacing()` method. This method returns a reference to a `FixedArray`. The returned object can then be used to read the contents of the array. Note the use of the `const` keyword to indicate that the array will not be modified.

```
const ImageType::SpacingType& sp = image->GetSpacing();
```

```
std::cout << "Spacing = ";
std::cout << sp[0] << ", " << sp[1] << std::endl;
```

The image origin is managed in a similar way to the spacing. A `Point` of the appropriate dimension must first be allocated. The coordinates of the origin can then be assigned to every component. These coordinates correspond to the position of the first pixel of the image with respect to an arbitrary reference system in physical space. It is the user's responsibility to make sure that multiple images used in the same application are using a consistent reference system. This is extremely important in image registration applications.

The following code illustrates the creation and assignment of a variable suitable for initializing the image origin.

```
ImageType::PointType origin;

origin[0] = 0.0;  // coordinates of the
origin[1] = 0.0;  // first pixel in 2-D

image->SetOrigin(origin);
```

The origin can also be retrieved from an image by using the `GetOrigin()` method. This will return a reference to a `Point`. The reference can be used to read the contents of the array. Note again the use of the `const` keyword to indicate that the array contents will not be modified.

```
const ImageType::PointType& orgn = image->GetOrigin();

std::cout << "Origin = ";
std::cout << orgn[0] << ", " << orgn[1] << std::endl;
```

Once the spacing and origin of the image have been initialized, the image will correctly map pixel indices to and from physical space coordinates. The following code illustrates how a point in physical space can be mapped into an image index for the purpose of reading the content of the closest pixel.

First, a `itk::Point` type must be declared. The point type is templated over the type used to represent coordinates and over the dimension of the space. In this particular case, the dimension of the point must match the dimension of the image.

```
typedef itk::Point<double, ImageType::ImageDimension> PointType;
```

The Point class, like an `itk::Index`, is a relatively small and simple object. For this reason, it is not reference-counted like the large data objects in OTB. Consequently, it is also not manipulated with `itk::SmartPointer`s. Point objects are simply declared as instances of any other C++ class. Once the point is declared, its components can be accessed using traditional array notation. In particular, the `[]` operator is available. For efficiency reasons, no bounds checking is performed on the index used to access a particular point component. It is the user's responsibility to make sure that the index is in the range $\{0, Dimension - 1\}$.

```
PointType point;

point[0] = 1.45;    // x coordinate
point[1] = 7.21;    // y coordinate
```

The image will map the point to an index using the values of the current spacing and origin. An index object must be provided to receive the results of the mapping. The index object can be instantiated by using the `IndexType` defined in the Image type.

```
ImageType::IndexType pixelIndex;
```

The `TransformPhysicalPointToIndex()` method of the image class will compute the pixel index closest to the point provided. The method checks for this index to be contained inside the current buffered pixel data. The method returns a boolean indicating whether the resulting index falls inside the buffered region or not. The output index should not be used when the returned value of the method is `false`.

The following lines illustrate the point to index mapping and the subsequent use of the pixel index for accessing pixel data from the image.

```
bool isInside = image->TransformPhysicalPointToIndex(point, pixelIndex);

if (isInside)
  {
  ImageType::PixelType pixelValue = image->GetPixel(pixelIndex);

  pixelValue += 5;

  image->SetPixel(pixelIndex, pixelValue);
  }
```

Remember that `GetPixel()` and `SetPixel()` are very inefficient methods for accessing pixel data. Image iterators should be used when massive access to pixel data is required.

5.1.5 Accessing Image Metadata

The source code for this example can be found in the file
`Examples/IO/MetadataExample.cxx`.

This example illustrates the access to metadata image information with OTB. By metadata, we mean data which is typically stored with remote sensing images, like geographical coordinates of pixels, pixel spacing or resolution, etc. Of course, the availability of these data depends on the image format used and on the fact that the image producer must fill the available metadata fields. The image formats which typically support metadata are for example CEOS and GeoTiff.

The metadata support is embedded in OTB's IO functionnalities and is accessible through the `otb::Image` and `otb::VectorImage` classes. You should avoid using the `itk::Image` class if

you want to have metadata support.

This simple example will consist on reading an image from a file and writing the metadata to an output ASCII file. As usual we start by defining the types needed for the image to be read.

```
typedef unsigned char InputPixelType;
const unsigned int Dimension = 2;

typedef otb::Image<InputPixelType,  Dimension> InputImageType;

typedef otb::ImageFileReader<InputImageType> ReaderType;
```

We can now instantiate the reader and get a pointer to the input image.

```
ReaderType::Pointer     reader = ReaderType::New();
InputImageType::Pointer image = InputImageType::New();

reader->SetFileName(inputFilename);
reader->Update();

image = reader->GetOutput();
```

Once the image has been read, we can access the metadata information. We will copy this information to an ASCII file, so we create an output file stream for this purpose.

```
std::ofstream file;

file.open(outputAsciiFilename);
```

We can now call the different available methods for accessing the metadata. Useful methods are :

- `GetSpacing`: the sampling step;
- `GetOrigin`: the coordinates of the origin of the image;
- `GetProjectionRef`: the image projection reference;
- `GetGCPProjection`: the projection for the eventual ground control points;
- `GetGCPCount`: the number of GCPs available;

```
file << "Spacing " << image->GetSpacing() << std::endl;
file << "Origin " << image->GetOrigin() << std::endl;

file << "Projection REF " << image->GetProjectionRef() << std::endl;

file << "GCP Projection " << image->GetGCPProjection() << std::endl;

unsigned int GCPCount = image->GetGCPCount();
file << "GCP Count " << image->GetGCPCount() << std::endl;
```

One can also get the GCPs by number, as well as their coordinates in image and geographical space.

```
for (unsigned int GCPnum = 0; GCPnum < GCPCount; GCPnum++)
  {
  file << "GCP[" << GCPnum << "] Id " << image->GetGCPId(GCPnum) << std::endl;
  file << "GCP[" << GCPnum << "] Info " << image->GetGCPInfo(GCPnum) <<
  std::endl;
  file << "GCP[" << GCPnum << "] Row " << image->GetGCPRow(GCPnum) <<
  std::endl;
  file << "GCP[" << GCPnum << "] Col " << image->GetGCPCol(GCPnum) <<
  std::endl;
  file << "GCP[" << GCPnum << "] X " << image->GetGCPX(GCPnum) << std::endl;
  file << "GCP[" << GCPnum << "] Y " << image->GetGCPY(GCPnum) << std::endl;
  file << "GCP[" << GCPnum << "] Z " << image->GetGCPZ(GCPnum) << std::endl;
  file << "----------------" << std::endl;
  }
```

If a geographical transformation is available, it can be recovered as follows.

```
InputImageType::VectorType tab = image->GetGeoTransform();

file << "Geo Transform " << std::endl;
for (unsigned int i = 0; i < tab.size(); ++i)
  {
  file << " " << i << " -> " << tab[i] << std::endl;
  }
tab.clear();

tab = image->GetUpperLeftCorner();
file << "Corners " << std::endl;
for (unsigned int i = 0; i < tab.size(); ++i)
  {
  file << " UL[" << i << "] -> " << tab[i] << std::endl;
  }
tab.clear();

tab = image->GetUpperRightCorner();
for (unsigned int i = 0; i < tab.size(); ++i)
  {
  file << " UR[" << i << "] -> " << tab[i] << std::endl;
  }
tab.clear();

tab = image->GetLowerLeftCorner();
for (unsigned int i = 0; i < tab.size(); ++i)
  {
  file << " LL[" << i << "] -> " << tab[i] << std::endl;
  }
tab.clear();

tab = image->GetLowerRightCorner();
for (unsigned int i = 0; i < tab.size(); ++i)
  {
  file << " LR[" << i << "] -> " << tab[i] << std::endl;
  }
```

```
tab.clear();

file.close();
```

5.1.6 RGB Images

The term RGB (Red, Green, Blue) stands for a color representation commonly used in digital imaging. RGB is a representation of the human physiological capability to analyze visual light using three spectral-selective sensors [91, 145]. The human retina possess different types of light sensitive cells. Three of them, known as *cones*, are sensitive to color [51] and their regions of sensitivity loosely match regions of the spectrum that will be perceived as red, green and blue respectively. The *rods* on the other hand provide no color discrimination and favor high resolution and high sensitivity[1]. A fifth type of receptors, the *ganglion cells*, also known as circadian[2] receptors are sensitive to the lighting conditions that differentiate day from night. These receptors evolved as a mechanism for synchronizing the physiology with the time of the day. Cellular controls for circadian rythms are present in every cell of an organism and are known to be exquisitively precise [88].

The RGB space has been constructed as a representation of a physiological response to light by the three types of *cones* in the human eye. RGB is not a Vector space. For example, negative numbers are not appropriate in a color space because they will be the equivalent of "negative stimulation" on the human eye. In the context of colorimetry, negative color values are used as an artificial construct for color comparison in the sense that

$$ColorA = ColorB - ColorC \tag{5.1}$$

just as a way of saying that we can produce $ColorB$ by combining $ColorA$ and $ColorC$. However, we must be aware that (at least in emitted light) it is not possible to *substract light*. So when we mention Equation 5.1 we actually mean

$$ColorB = ColorA + ColorC \tag{5.2}$$

On the other hand, when dealing with printed color and with paint, as opposed to emitted light like in computer screens, the physical behavior of color allows for subtraction. This is because strictly speaking the objects that we see as red are those that absorb all light frequencies except those in the red section of the spectrum [145].

The concept of addition and subtraction of colors has to be carefully interpreted. In fact, RGB has a different definition regarding whether we are talking about the channels associated to the three color sensors of the human eye, or to the three phosphors found in most computer monitors or to the color inks that are used for printing reproduction. Color spaces are usually non linear and do not even from a Group. For example, not all visible colors can be represented in RGB space [145].

[1] The human eye is capable of perceiving a single isolated photon.

[2] The term *Circadian* refers to the cycle of day and night, that is, events that are repeated with 24 hours intervals.

ITK introduces the `itk::RGBPixel` type as a support for representing the values of an RGB color space. As such, the RGBPixel class embodies a different concept from the one of an `itk::Vector` in space. For this reason, the RGBPixel lack many of the operators that may be naively expected from it. In particular, there are no defined operations for subtraction or addition.

When you anticipate to perform the operation of "Mean" on a RGB type you are assuming that in the color space provides the action of finding a color in the middle of two colors, can be found by using a linear operation between their numerical representation. This is unfortunately not the case in color spaces due to the fact that they are based on a human physiological response [91].

If you decide to interpret RGB images as simply three independent channels then you should rather use the `itk::Vector` type as pixel type. In this way, you will have access to the set of operations that are defined in Vector spaces. The current implementation of the RGBPixel in ITK presumes that RGB color images are intended to be used in applications where a formal interpretation of color is desired, therefore only the operations that are valid in a color space are available in the RGBPixel class.

The following example illustrates how RGB images can be represented in OTB.

The source code for this example can be found in the file
`Examples/DataRepresentation/Image/RGBImage.cxx`.

Thanks to the flexibility offered by the Generic Programming style on which OTB is based, it is possible to instantiate images of arbitrary pixel type. The following example illustrates how a color image with RGB pixels can be defined.

A class intended to support the RGB pixel type is available in ITK. You could also define your own pixel class and use it to instantiate a custom image type. In order to use the `itk::RGBPixel` class, it is necessary to include its header file.

```
#include "itkRGBPixel.h"
```

The RGB pixel class is templated over a type used to represent each one of the red, green and blue pixel components. A typical instantiation of the templated class is as follows.

```
  typedef itk::RGBPixel<unsigned char> PixelType;
```

The type is then used as the pixel template parameter of the image.

```
  typedef otb::Image<PixelType, 2> ImageType;
```

The image type can be used to instantiate other filter, for example, an `otb::ImageFileReader` object that will read the image from a file.

```
  typedef otb::ImageFileReader<ImageType> ReaderType;
```

Access to the color components of the pixels can now be performed using the methods provided by the RGBPixel class.

```
PixelType onePixel = image->GetPixel(pixelIndex);

PixelType::ValueType red   = onePixel.GetRed();
PixelType::ValueType green = onePixel.GetGreen();
PixelType::ValueType blue  = onePixel.GetBlue();
```

The subindex notation can also be used since the `itk::RGBPixel` inherits the `[]` operator from the `itk::FixedArray` class.

```
red   = onePixel[0];  // extract Red   component
green = onePixel[1];  // extract Green component
blue  = onePixel[2];  // extract Blue  component

std::cout << "Pixel values:" << std::endl;
std::cout << "Red = "
          << itk::NumericTraits<PixelType::ValueType>::PrintType(red)
          << std::endl;
std::cout << "Green = "
          << itk::NumericTraits<PixelType::ValueType>::PrintType(green)
          << std::endl;
std::cout << "Blue = "
          << itk::NumericTraits<PixelType::ValueType>::PrintType(blue)
          << std::endl;
```

5.1.7 Vector Images

The source code for this example can be found in the file `Examples/DataRepresentation/Image/VectorImage.cxx`.

Many image processing tasks require images of non-scalar pixel type. A typical example is a multi-spectral image. The following code illustrates how to instantiate and use an image whose pixels are of vector type.

We could use the `itk::Vector` class to define the pixel type. The Vector class is intended to represent a geometrical vector in space. It is not intended to be used as an array container like the `std::vector` in STL. If you are interested in containers, the `itk::VectorContainer` class may provide the functionality you want.

However, the `itk::Vector` is a fixed size array and it assumes that the number of channels of the image is known at compile time. Therefore, we prefer to use the `otb::VectorImage` class which allows to choose the number of channels of the image at runtime. The pixels will be of type `itk::VariableLengthVector`.

The first step is to include the header file of the VectorImage class.

```
#include "otbVectorImage.h"
```

The VectorImage class is templated over the type used to represent the coordinate in space and over the dimension of the space. In this example, we want to represent Pléiades images which have 4 bands.

```
typedef unsigned char                  PixelType;
typedef otb::VectorImage<PixelType, 2> ImageType;
```

Since the pixel dimensionality is choosen at runtime, one has to pass this parameter to the image before memory allocation.

```
image->SetNumberOfComponentsPerPixel(4);
image->Allocate();
```

The VariableLengthVector class overloads the operator `[]`. This makes it possible to access the Vector's components using index notation. The user must not forget to allocate the memory for each individual pixel by using the `Reserve` method.

```
ImageType::PixelType pixelValue;
pixelValue.Reserve(4);

pixelValue[0] =  1;   // Blue component
pixelValue[1] =  6;   // Green component
pixelValue[2] =  100; // Red component
pixelValue[3] =  100; // NIR component
```

We can now store this vector in one of the image pixels by defining an index and invoking the `SetPixel()` method.

```
image->SetPixel(pixelIndex,   pixelValue);
```

The GetPixel method can also be used to read Vectors pixels from the image

```
ImageType::PixelType value = image->GetPixel(pixelIndex);
```

Lets repeat that both `SetPixel()` and `GetPixel()` are inefficient and should only be used for debugging purposes or for implementing interactions with a graphical user interface such as querying pixel value by clicking with the mouse.

5.1.8 Importing Image Data from a Buffer

The source code for this example can be found in the file
`Examples/DataRepresentation/Image/Image5.cxx`.

This example illustrates how to import data into the `otb::Image` class. This is particularly useful for interfacing with other software systems. Many systems use a contiguous block of memory as a buffer for image pixel data. The current example assumes this is the case and feeds the buffer into an `otb::ImportImageFilter`, thereby producing an Image as output.

For fun we create a synthetic image with a centered sphere in a locally allocated buffer and pass this block of memory to the ImportImageFilter. This example is set up so that on execution, the user must provide the name of an output file as a command-line argument.

First, the header file of the ImportImageFilter class must be included.

```
#include "otbImage.h"
#include "otbImportImageFilter.h"
```

Next, we select the data type to use to represent the image pixels. We assume that the external block of memory uses the same data type to represent the pixels.

```
typedef unsigned char PixelType;
const unsigned int Dimension = 2;
typedef otb::Image<PixelType, Dimension> ImageType;
```

The type of the ImportImageFilter is instantiated in the following line.

```
typedef otb::ImportImageFilter<ImageType> ImportFilterType;
```

A filter object created using the `New()` method is then assigned to a `SmartPointer`.

```
ImportFilterType::Pointer importFilter = ImportFilterType::New();
```

This filter requires the user to specify the size of the image to be produced as output. The `SetRegion()` method is used to this end. The image size should exactly match the number of pixels available in the locally allocated buffer.

```
ImportFilterType::SizeType size;

size[0]  = 200;  // size along X
size[1]  = 200;  // size along Y

ImportFilterType::IndexType start;
start.Fill(0);

ImportFilterType::RegionType region;
region.SetIndex(start);
region.SetSize(size);

importFilter->SetRegion(region);
```

The origin of the output image is specified with the `SetOrigin()` method.

```
double origin[Dimension];
origin[0] = 0.0;    // X coordinate
origin[1] = 0.0;    // Y coordinate

importFilter->SetOrigin(origin);
```

The spacing of the image is passed with the `SetSpacing()` method.

```
double spacing[Dimension];
spacing[0] = 1.0;    // along X direction
spacing[1] = 1.0;    // along Y direction

importFilter->SetSpacing(spacing);
```

Next we allocate the memory block containing the pixel data to be passed to the ImportImageFilter. Note that we use exactly the same size that was specified with the `SetRegion()` method. In a practical application, you may get this buffer from some other library using a different data structure to represent the images.

```
// MODIFIED
const unsigned int numberOfPixels =  size[0] * size[1];
PixelType *        localBuffer = new PixelType[numberOfPixels];
```

Here we fill up the buffer with a binary sphere. We use simple `for()` loops here similar to those found in the C or FORTRAN programming languages. Note that otb does not use `for()` loops in its internal code to access pixels. All pixel access tasks are instead performed using `otb::ImageIterator`s that support the management of n-dimensional images.

```
const double radius2 = radius * radius;
PixelType *  it = localBuffer;

for (unsigned int y = 0; y < size[1]; y++)
  {
  const double dy = static_cast<double>(y) - static_cast<double>(size[1]) /
                    2.0;
  for (unsigned int x = 0; x < size[0]; x++)
    {
    const double dx = static_cast<double>(x) - static_cast<double>(size[0]) /
                      2.0;
    const double d2 = dx * dx + dy * dy;
    *it++ = (d2 < radius2) ? 255 : 0;
    }
  }
```

The buffer is passed to the ImportImageFilter with the `SetImportPointer()`. Note that the last argument of this method specifies who will be responsible for deleting the memory block once it is no longer in use. A `false` value indicates that the ImportImageFilter will not try to delete the buffer when its destructor is called. A `true` value, on the other hand, will allow the filter to delete the memory block upon destruction of the import filter.

For the ImportImageFilter to appropriately delete the memory block, the memory must be allocated with the C++ `new()` operator. Memory allocated with other memory allocation mechanisms, such as C `malloc` or `calloc`, will not be deleted properly by the ImportImageFilter. In other words, it is the application programmer's responsibility to ensure that ImportImageFilter is only given permission to delete the C++ `new` operator-allocated memory.

```
const bool importImageFilterWillOwnTheBuffer = true;
importFilter->SetImportPointer(localBuffer, numberOfPixels,
```

```
                                    importImageFilterWillOwnTheBuffer);
```

Finally, we can connect the output of this filter to a pipeline. For simplicity we just use a writer here, but it could be any other filter.

```
writer->SetInput(dynamic_cast<ImageType*>(importFilter->GetOutput()));
```

Note that we do not call `delete` on the buffer since we pass `true` as the last argument of `SetImportPointer()`. Now the buffer is owned by the ImportImageFilter.

5.1.9 Image Lists

The source code for this example can be found in the file `Examples/DataRepresentation/Image/ImageListExample.cxx`.

This example illustrates the use of the `otb::ImageList::c`lass. This class provides the functionnalities needed in order to integrate image lists as data objects into the OTB pipeline. Indeed, if a `std::list< ImageType >` was used, the update operations on the pipeline might not have the desired effects.

In this example, we will only present the basic operations which can be applied on an `otb::ImageList::o`bject.

The first thing required to read an image from a file is to include the header file of the `otb::ImageFileReader::c`lass.

```
#include "otbImageList.h"
```

As usual, we start by defining the types for the pixel and image types, as well as those for the readers and writers.

```
const unsigned int Dimension = 2;
typedef unsigned char                          InputPixelType;
typedef otb::Image<InputPixelType, Dimension> InputImageType;
typedef otb::ImageFileReader<InputImageType>  ReaderType;
typedef otb::ImageFileWriter<InputImageType>  WriterType;
```

We can now define the type for the image list. The `otb::ImageList::c`lass is templated over the type of image contained in it. This means that all images in a list must have the same type.

```
typedef otb::ImageList<InputImageType> ImageListType;
```

Let us assume now that we want to read an image from a file and store it in a list. The first thing to do is to instantiate the reader and set the image file name. We effectively read the image by calling the `Update()`.

```
ReaderType::Pointer reader = ReaderType::New();
```

```
  reader->SetFileName(inputFilename);
  reader->Update();
```

We create an image list by using the `New()` method.

```
  ImageListType::Pointer imageList = ImageListType::New();
```

In order to store the image in the list, the `PushBack()` method is used.

```
  imageList->PushBack(reader->GetOutput());
```

We could repeat this operation for other readers or the outputs of filters. We will now write an image of the list to a file. We therefore instantiate a writer, set the image file name and set the input image for it. This is done by calling the `Back()` method of the list, which allows us to get the last element.

```
// Getting the image from the list and writing it to file
  WriterType::Pointer writer = WriterType::New();
  writer->SetFileName(outputFilename);
  writer->SetInput(imageList->Back());
  writer->Update();
```

Other useful methods are:

- `SetNthElement()` and `GetNthElement()` allow to randomly access any element of the list.
- `Front()` to access to the first element of the list.
- `Erase()` to remove an element.

Also, iterator classes are defined in order to have an efficient mean of moving through the list. Finally, the `otb::ImageListToImageListFilter::i`s provided in order to implement filter which operate on image lists and produce image lists.

5.2 PointSet

5.2.1 Creating a PointSet

The source code for this example can be found in the file
`Examples/DataRepresentation/Mesh/PointSet1.cxx`.

The `itk::PointSet` is a basic class intended to represent geometry in the form of a set of points in n-dimensional space. It is the base class for the `itk::Mesh` providing the methods necessary to manipulate sets of point. Points can have values associated with them. The type of such values is defined by a template parameter of the `itk::PointSet` class (i.e., `TPixelType`. Two basic interaction styles of PointSets are available in ITK. These styles are referred to as *static* and *dynamic*.

The first style is used when the number of points in the set is known in advance and is not expected to change as a consequence of the manipulations performed on the set. The dynamic style, on the other hand, is intended to support insertion and removal of points in an efficient manner. Distinguishing between the two styles is meant to facilitate the fine tuning of a `PointSet`'s behavior while optimizing performance and memory management.

In order to use the PointSet class, its header file should be included.

```
#include "itkPointSet.h"
```

Then we must decide what type of value to associate with the points. This is generally called the `PixelType` in order to make the terminology consistent with the `itk::Image`. The PointSet is also templated over the dimension of the space in which the points are represented. The following declaration illustrates a typical instantiation of the PointSet class.

```
typedef itk::PointSet<unsigned short, 2> PointSetType;
```

A `PointSet` object is created by invoking the `New()` method on its type. The resulting object must be assigned to a `SmartPointer`. The PointSet is then reference-counted and can be shared by multiple objects. The memory allocated for the PointSet will be released when the number of references to the object is reduced to zero. This simply means that the user does not need to be concerned with invoking the `Delete()` method on this class. In fact, the `Delete()` method should **never** be called directly within any of the reference-counted ITK classes.

```
PointSetType::Pointer pointsSet = PointSetType::New();
```

Following the principles of Generic Programming, the `PointSet` class has a set of associated defined types to ensure that interacting objects can be declared with compatible types. This set of type definitions is commonly known as a set of *traits*. Among them we can find the `PointType` type, for example. This is the type used by the point set to represent points in space. The following declaration takes the point type as defined in the `PointSet` traits and renames it to be conveniently used in the global namespace.

```
typedef PointSetType::PointType PointType;
```

The `PointType` can now be used to declare point objects to be inserted in the `PointSet`. Points are fairly small objects, so it is inconvenient to manage them with reference counting and smart pointers. They are simply instantiated as typical C++ classes. The Point class inherits the `[]` operator from the `itk::Array` class. This makes it possible to access its components using index notation. For efficiency's sake no bounds checking is performed during index access. It is the user's responsibility to ensure that the index used is in the range $\{0, Dimension - 1\}$. Each of the components in the point is associated with space coordinates. The following code illustrates how to instantiate a point and initialize its components.

```
PointType p0;
p0[0] = -1.0;     //  x coordinate
p0[1] = -1.0;     //  y coordinate
```

Points are inserted in the PointSet by using the `SetPoint()` method. This method requires the user to provide a unique identifier for the point. The identifier is typically an unsigned integer that will enumerate the points as they are being inserted. The following code shows how three points are inserted into the PointSet.

```
pointsSet->SetPoint(0, p0);
pointsSet->SetPoint(1, p1);
pointsSet->SetPoint(2, p2);
```

It is possible to query the PointSet in order to determine how many points have been inserted into it. This is done with the `GetNumberOfPoints()` method as illustrated below.

```
const unsigned int numberOfPoints = pointsSet->GetNumberOfPoints();
std::cout << numberOfPoints << std::endl;
```

Points can be read from the PointSet by using the `GetPoint()` method and the integer identifier. The point is stored in a pointer provided by the user. If the identifier provided does not match an existing point, the method will return `false` and the contents of the point will be invalid. The following code illustrates point access using defensive programming.

```
PointType pp;
bool      pointExists =  pointsSet->GetPoint(1, &pp);

if (pointExists)
  {
  std::cout << "Point is = " << pp << std::endl;
  }
```

`GetPoint()` and `SetPoint()` are not the most efficient methods to access points in the PointSet. It is preferable to get direct access to the internal point container defined by the *traits* and use iterators to walk sequentially over the list of points (as shown in the following example).

5.2.2 Getting Access to Points

The source code for this example can be found in the file
`Examples/DataRepresentation/Mesh/PointSet2.cxx`.

The `itk::PointSet` class uses an internal container to manage the storage of `itk::Point`s. It is more efficient, in general, to manage points by using the access methods provided directly on the points container. The following example illustrates how to interact with the point container and how to use point iterators.

The type is defined by the *traits* of the PointSet class. The following line conveniently takes the PointsContainer type from the PointSet traits and declare it in the global namespace.

```
typedef PointSetType::PointsContainer PointsContainer;
```

The actual type of the PointsContainer depends on what style of PointSet is being used. The dynamic PointSet use the `itk::MapContainer` while the static PointSet uses the `itk::VectorContainer`. The vector and map containers are basically ITK wrappers around the STL classes `std::map` and `std::vector`. By default, the PointSet uses a static style, hence the default type of point container is an VectorContainer. Both the map and vector container are templated over the type of the elements they contain. In this case they are templated over PointType. Containers are reference counted object. They are then created with the `New()` method and assigned to a `itk::SmartPointer` after creation. The following line creates a point container compatible with the type of the PointSet from which the trait has been taken.

```
PointsContainer::Pointer points = PointsContainer::New();
```

Points can now be defined using the `PointType` trait from the PointSet.

```
typedef PointSetType::PointType PointType;
PointType p0;
PointType p1;
p0[0] = -1.0;
p0[1] = 0.0;  // Point 0 = {-1, 0 }
p1[0] =  1.0;
p1[1] = 0.0;  // Point 1 = { 1, 0 }
```

The created points can be inserted in the PointsContainer using the generic method `InsertElement()` which requires an identifier to be provided for each point.

```
unsigned int pointId = 0;
points->InsertElement(pointId++, p0);
points->InsertElement(pointId++, p1);
```

Finally the PointsContainer can be assigned to the PointSet. This will substitute any previously existing PointsContainer on the PointSet. The assignment is done using the `SetPoints()` method.

```
pointSet->SetPoints(points);
```

The PointsContainer object can be obtained from the PointSet using the `GetPoints()` method. This method returns a pointer to the actual container owned by the PointSet which is then assigned to a SmartPointer.

```
PointsContainer::Pointer points2 = pointSet->GetPoints();
```

The most efficient way to sequentially visit the points is to use the iterators provided by PointsContainer. The `Iterator` type belongs to the traits of the PointsContainer classes. It behaves pretty much like the STL iterators.[3] The Points iterator is not a reference counted class, so it is created directly from the traits without using SmartPointers.

```
typedef PointsContainer::Iterator PointsIterator;
```

[3] If you dig deep enough into the code, you will discover that these iterators are actually ITK wrappers around STL iterators.

The subsequent use of the iterator follows what you may expect from a STL iterator. The iterator to the first point is obtained from the container with the `Begin()` method and assigned to another iterator.

```
PointsIterator pointIterator = points->Begin();
```

The ++ operator on the iterator can be used to advance from one point to the next. The actual value of the Point to which the iterator is pointing can be obtained with the `Value()` method. The loop for walking through all the points can be controlled by comparing the current iterator with the iterator returned by the `End()` method of the PointsContainer. The following lines illustrate the typical loop for walking through the points.

```
PointsIterator end = points->End();
while (pointIterator != end)
  {
  PointType p = pointIterator.Value();   // access the point
  std::cout << p << std::endl;           // print the point
  ++pointIterator;                       // advance to next point
  }
```

Note that as in STL, the iterator returned by the `End()` method is not a valid iterator. This is called a past-end iterator in order to indicate that it is the value resulting from advancing one step after visiting the last element in the container.

The number of elements stored in a container can be queried with the `Size()` method. In the case of the PointSet, the following two lines of code are equivalent, both of them returning the number of points in the PointSet.

```
std::cout << pointSet->GetNumberOfPoints() << std::endl;
std::cout << pointSet->GetPoints()->Size() << std::endl;
```

5.2.3 Getting Access to Data in Points

The source code for this example can be found in the file
`Examples/DataRepresentation/Mesh/PointSet3.cxx`.

The `itk::PointSet` class was designed to interact with the Image class. For this reason it was found convenient to allow the points in the set to hold values that could be computed from images. The value associated with the point is referred as `PixelType` in order to make it consistent with image terminology. Users can define the type as they please thanks to the flexibility offered by the Generic Programming approach used in the toolkit. The `PixelType` is the first template parameter of the PointSet.

The following code defines a particular type for a pixel type and instantiates a PointSet class with it.

```
typedef unsigned short              PixelType;
typedef itk::PointSet<PixelType, 2> PointSetType;
```

Data can be inserted into the PointSet using the SetPointData() method. This method requires the user to provide an identifier. The data in question will be associated to the point holding the same identifier. It is the user's responsibility to verify the appropriate matching between inserted data and inserted points. The following line illustrates the use of the SetPointData() method.

```
unsigned int dataId =  0;
PixelType    value     = 79;
pointSet->SetPointData(dataId++, value);
```

Data associated with points can be read from the PointSet using the GetPointData() method. This method requires the user to provide the identifier to the point and a valid pointer to a location where the pixel data can be safely written. In case the identifier does not match any existing identifier on the PointSet the method will return false and the pixel value returned will be invalid. It is the user's responsibility to check the returned boolean value before attempting to use it.

```
const bool found = pointSet->GetPointData(dataId, &value);
if (found)
  {
  std::cout << "Pixel value = " << value << std::endl;
  }
```

The SetPointData() and GetPointData() methods are not the most efficient way to get access to point data. It is far more efficient to use the Iterators provided by the PointDataContainer.

Data associated with points is internally stored in PointDataContainers. In the same way as with points, the actual container type used depend on whether the style of the PointSet is static or dynamic. Static point sets will use an itk::VectorContainer while dynamic point sets will use an itk::MapContainer. The type of the data container is defined as one of the traits in the PointSet. The following declaration illustrates how the type can be taken from the traits and used to conveniently declare a similar type on the global namespace.

```
typedef PointSetType::PointDataContainer PointDataContainer;
```

Using the type it is now possible to create an instance of the data container. This is a standard reference counted object, henceforth it uses the New() method for creation and assigns the newly created object to a SmartPointer.

```
PointDataContainer::Pointer pointData = PointDataContainer::New();
```

Pixel data can be inserted in the container with the method InsertElement(). This method requires an identified to be provided for each point data.

```
unsigned int pointId = 0;

PixelType value0 = 34;
PixelType value1 = 67;

pointData->InsertElement(pointId++, value0);
pointData->InsertElement(pointId++, value1);
```

Finally the PointDataContainer can be assigned to the PointSet. This will substitute any previously existing PointDataContainer on the PointSet. The assignment is done using the `SetPointData()` method.

```
pointSet->SetPointData(pointData);
```

The PointDataContainer can be obtained from the PointSet using the `GetPointData()` method. This method returns a pointer (assigned to a SmartPointer) to the actual container owned by the PointSet.

```
PointDataContainer::Pointer pointData2 = pointSet->GetPointData();
```

The most efficient way to sequentially visit the data associated with points is to use the iterators provided by `PointDataContainer`. The `Iterator` type belongs to the traits of the PointsContainer classes. The iterator is not a reference counted class, so it is just created directly from the traits without using SmartPointers.

```
typedef PointDataContainer::Iterator PointDataIterator;
```

The subsequent use of the iterator follows what you may expect from a STL iterator. The iterator to the first point is obtained from the container with the `Begin()` method and assigned to another iterator.

```
PointDataIterator pointDataIterator = pointData2->Begin();
```

The ++ operator on the iterator can be used to advance from one data point to the next. The actual value of the PixelType to which the iterator is pointing can be obtained with the `Value()` method. The loop for walking through all the point data can be controlled by comparing the current iterator with the iterator returned by the `End()` method of the PointsContainer. The following lines illustrate the typical loop for walking through the point data.

```
PointDataIterator end = pointData2->End();
while (pointDataIterator != end)
  {
  PixelType p = pointDataIterator.Value();  // access the pixel data
  std::cout << p << std::endl;              // print the pixel data
  ++pointDataIterator;                      // advance to next pixel/point
  }
```

Note that as in STL, the iterator returned by the `End()` method is not a valid iterator. This is called a *past-end* iterator in order to indicate that it is the value resulting from advancing one step after visiting the last element in the container.

5.2.4 Vectors as Pixel Type

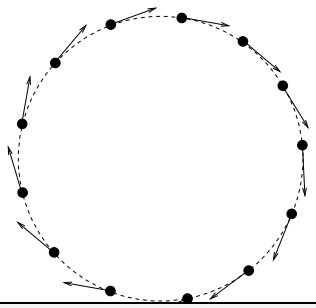
The source code for this example can be found in the file
`Examples/DataRepresentation/Mesh/PointSetWithVectors.cxx`.

This example illustrates how a point set can be parameterized to manage a particular pixel type. It is quite common to associate vector values with points for producing geometric representations or storing multi-band informations. The following code shows how vector values can be used as pixel type on the PointSet class. The `itk::Vector` class is used here as the pixel type. This class is appropriate for representing the relative position between two points. It could then be used to manage displacements in disparity map estimations, for example.

In order to use the vector class it is necessary to include its header file along with the header of the point set.

```
#include "itkVector.h"
#include "itkPointSet.h"
```

The Vector class is templated over the type used to represent the spatial coordinates and over the space dimension. Since the PixelType is independent of the PointType, we are free to select any dimension for the vectors to be used as pixel type. However, for the sake of producing an interesting example, we will use vectors that represent displacements of the points in the PointSet. Those vectors are then selected to be of the same dimension as the PointSet.



```
const unsigned int Dimension = 2;
typedef itk::Vector<float, Dimension> PixelType;
```

Then we use the PixelType (which are actually Vectors) to instantiate the PointSet type and subsequently create a PointSet object.

```
typedef itk::PointSet<PixelType, Dimension> PointSetType;
PointSetType::Pointer pointSet = PointSetType::New();
```

The following code is generating a circle and assigning vector values to the points. The components of the vectors in this example are computed to represent the tangents to the circle as shown in Figure 5.2.

```
PointSetType::PixelType tangent;
PointSetType::PointType point;

unsigned int pointId =  0;
const double radius = 300.0;

for (unsigned int i = 0; i < 360; ++i)
  {
  const double angle = i * atan(1.0) / 45.0;
  point[0] = radius * sin(angle);
  point[1] = radius * cos(angle);
  tangent[0] =  cos(angle);
  tangent[1] = -sin(angle);
```

```
  pointSet->SetPoint(pointId, point);
  pointSet->SetPointData(pointId, tangent);
  pointId++;
  }
```

We can now visit all the points and use the vector on the pixel values to apply a displacement on the points. This is along the spirit of what a deformable model could do at each one of its iterations.

```
typedef  PointSetType::PointDataContainer::ConstIterator PointDataIterator;
PointDataIterator pixelIterator = pointSet->GetPointData()->Begin();
PointDataIterator pixelEnd      = pointSet->GetPointData()->End();

typedef  PointSetType::PointsContainer::Iterator PointIterator;
PointIterator pointIterator = pointSet->GetPoints()->Begin();
PointIterator pointEnd      = pointSet->GetPoints()->End();

while (pixelIterator != pixelEnd  && pointIterator != pointEnd)
  {
  pointIterator.Value() = pointIterator.Value() + pixelIterator.Value();
  ++pixelIterator;
  ++pointIterator;
  }
```

Note that the `ConstIterator` was used here instead of the normal `Iterator` since the pixel values are only intended to be read and not modified. ITK supports const-correctness at the API level.

The `itk::Vector` class has overloaded the `+` operator with the `itk::Point`. In other words, vectors can be added to points in order to produce new points. This property is exploited in the center of the loop in order to update the points positions with a single statement.

We can finally visit all the points and print out the new values

```
pointIterator = pointSet->GetPoints()->Begin();
pointEnd      = pointSet->GetPoints()->End();
while (pointIterator != pointEnd)
  {
  std::cout << pointIterator.Value() << std::endl;
  ++pointIterator;
  }
```

Note that `itk::Vector` is not the appropriate class for representing normals to surfaces and gradients of functions. This is due to the way in which vectors behave under affine transforms. ITK has a specific class for representing normals and function gradients. This is the `itk::CovariantVector` class.

5.3 Mesh

5.3.1 Creating a Mesh

The source code for this example can be found in the file
`Examples/DataRepresentation/Mesh/Mesh1.cxx`.

The `itk::Mesh` class is intended to represent shapes in space. It derives from the `itk::PointSet` class and hence inherits all the functionality related to points and access to the pixel-data associated with the points. The mesh class is also n-dimensional which allows a great flexibility in its use.

In practice a Mesh class can be seen as a PointSet to which cells (also known as elements) of many different dimensions and shapes have been added. Cells in the mesh are defined in terms of the existing points using their point-identifiers.

In the same way as for the PointSet, two basic styles of Meshes are available in ITK. They are referred to as *static* and *dynamic*. The first one is used when the number of points in the set can be known in advance and it is not expected to change as a consequence of the manipulations performed on the set. The dynamic style, on the other hand, is intended to support insertion and removal of points in an efficient manner. The reason for making the distinction between the two styles is to facilitate fine tuning its behavior with the aim of optimizing performance and memory management. In the case of the Mesh, the dynamic/static aspect is extended to the management of cells.

In order to use the Mesh class, its header file should be included.

```
#include "itkMesh.h"
```

Then, the type associated with the points must be selected and used for instantiating the Mesh type.

```
  typedef   float PixelType;
```

The Mesh type extensively uses the capabilities provided by Generic Programming. In particular the Mesh class is parameterized over the PixelType and the dimension of the space. PixelType is the type of the value associated with every point just as is done with the PointSet. The following line illustrates a typical instantiation of the Mesh.

```
  const unsigned int Dimension = 2;
  typedef itk::Mesh<PixelType, Dimension> MeshType;
```

Meshes are expected to take large amounts of memory. For this reason they are reference counted objects and are managed using SmartPointers. The following line illustrates how a mesh is created by invoking the `New()` method of the MeshType and the resulting object is assigned to a `itk::SmartPointer`.

```
  MeshType::Pointer mesh = MeshType::New();
```

The management of points in the Mesh is exactly the same as in the PointSet. The type point associated with the mesh can be obtained through the `PointType` trait. The following code shows

the creation of points compatible with the mesh type defined above and the assignment of values to its coordinates.

```
MeshType::PointType p0;
MeshType::PointType p1;
MeshType::PointType p2;
MeshType::PointType p3;

p0[0] = -1.0;
p0[1] = -1.0; // first  point ( -1, -1 )
p1[0] =  1.0;
p1[1] = -1.0; // second point (  1, -1 )
p2[0] =  1.0;
p2[1] =  1.0; // third  point (  1,  1 )
p3[0] = -1.0;
p3[1] =  1.0; // fourth point ( -1,  1 )
```

The points can now be inserted in the Mesh using the `SetPoint()` method. Note that points are copied into the mesh structure. This means that the local instances of the points can now be modified without affecting the Mesh content.

```
mesh->SetPoint(0, p0);
mesh->SetPoint(1, p1);
mesh->SetPoint(2, p2);
mesh->SetPoint(3, p3);
```

The current number of points in the Mesh can be queried with the `GetNumberOfPoints()` method.

```
std::cout << "Points = " << mesh->GetNumberOfPoints() << std::endl;
```

The points can now be efficiently accessed using the Iterator to the PointsContainer as it was done in the previous section for the PointSet. First, the point iterator type is extracted through the mesh traits.

```
typedef MeshType::PointsContainer::Iterator PointsIterator;
```

A point iterator is initialized to the first point with the `Begin()` method of the PointsContainer.

```
PointsIterator pointIterator = mesh->GetPoints()->Begin();
```

The ++ operator on the iterator is now used to advance from one point to the next. The actual value of the Point to which the iterator is pointing can be obtained with the `Value()` method. The loop for walking through all the points is controlled by comparing the current iterator with the iterator returned by the `End()` method of the PointsContainer. The following lines illustrate the typical loop for walking through the points.

```
PointsIterator end = mesh->GetPoints()->End();
while (pointIterator != end)
  {
  MeshType::PointType p = pointIterator.Value();  // access the point
```

```
    std::cout << p << std::endl;                    // print the point
    ++pointIterator;                                // advance to next point
    }
```

5.3.2 Inserting Cells

The source code for this example can be found in the file
`Examples/DataRepresentation/Mesh/Mesh2.cxx`.

A `itk::Mesh` can contain a variety of cell types. Typical cells are the `itk::LineCell`, `itk::TriangleCell`, `itk::QuadrilateralCell` and `itk::TetrahedronCell`. The latter will not be used very often in the remote sensing context. Additional flexibility is provided for managing cells at the price of a bit more of complexity than in the case of point management.

The following code creates a polygonal line in order to illustrate the simplest case of cell management in a Mesh. The only cell type used here is the LineCell. The header file of this class has to be included.

```
#include "itkLineCell.h"
```

In order to be consistent with the Mesh, cell types have to be configured with a number of custom types taken from the mesh traits. The set of traits relevant to cells are packaged by the Mesh class into the `CellType` trait. This trait needs to be passed to the actual cell types at the moment of their instantiation. The following line shows how to extract the Cell traits from the Mesh type.

```
  typedef MeshType::CellType CellType;
```

The LineCell type can now be instantiated using the traits taken from the Mesh.

```
  typedef itk::LineCell<CellType> LineType;
```

The main difference in the way cells and points are managed by the Mesh is that points are stored by copy on the PointsContainer while cells are stored in the CellsContainer using pointers. The reason for using pointers is that cells use C++ polymorphism on the mesh. This means that the mesh is only aware of having pointers to a generic cell which is the base class of all the specific cell types. This architecture makes it possible to combine different cell types in the same mesh. Points, on the other hand, are of a single type and have a small memory footprint, which makes it efficient to copy them directly into the container.

Managing cells by pointers add another level of complexity to the Mesh since it is now necessary to establish a protocol to make clear who is responsible for allocating and releasing the cells' memory. This protocol is implemented in the form of a specific type of pointer called the `CellAutoPointer`. This pointer, based on the `itk::AutoPointer`, differs in many respects from the SmartPointer. The CellAutoPointer has an internal pointer to the actual object and a boolean flag that indicates if the CellAutoPointer is responsible for releasing the cell memory whenever the time comes for

its own destruction. It is said that a `CellAutoPointer` *owns* the cell when it is responsible for its destruction. Many CellAutoPointer can point to the same cell but at any given time, only **one** CellAutoPointer can own the cell.

The `CellAutoPointer` trait is defined in the MeshType and can be extracted as illustrated in the following line.

```
typedef CellType::CellAutoPointer CellAutoPointer;
```

Note that the CellAutoPointer is pointing to a generic cell type. It is not aware of the actual type of the cell, which can be for example LineCell, TriangleCell or TetrahedronCell. This fact will influence the way in which we access cells later on.

At this point we can actually create a mesh and insert some points on it.

```
MeshType::Pointer mesh = MeshType::New();

MeshType::PointType p0;
MeshType::PointType p1;
MeshType::PointType p2;

p0[0] = -1.0;
p0[1] = 0.0;
p1[0] =  1.0;
p1[1] = 0.0;
p2[0] =  1.0;
p2[1] = 1.0;

mesh->SetPoint(0, p0);
mesh->SetPoint(1, p1);
mesh->SetPoint(2, p2);
```

The following code creates two CellAutoPointers and initializes them with newly created cell objects. The actual cell type created in this case is LineCell. Note that cells are created with the normal `new` C++ operator. The CellAutoPointer takes ownership of the received pointer by using the method `TakeOwnership()`. Even though this may seem verbose, it is necessary in order to make it explicit from the code that the responsibility of memory release is assumed by the AutoPointer.

```
CellAutoPointer line0;
CellAutoPointer line1;

line0.TakeOwnership(new LineType);
line1.TakeOwnership(new LineType);
```

The LineCells should now be associated with points in the mesh. This is done using the identifiers assigned to points when they were inserted in the mesh. Every cell type has a specific number of points that must be associated with it.[4] For example a LineCell requires two points, a TriangleCell requires three and a TetrahedronCell requires four. Cells use an internal numbering system for

[4] Some cell types like polygons have a variable number of points associated with them.

points. It is simply an index in the range $\{0, NumberOfPoints - 1\}$. The association of points and cells is done by the `SetPointId()` method which requires the user to provide the internal index of the point in the cell and the corresponding PointIdentifier in the Mesh. The internal cell index is the first parameter of `SetPointId()` while the mesh point-identifier is the second.

```
line0->SetPointId(0, 0);    // line between points 0 and 1
line0->SetPointId(1, 1);

line1->SetPointId(0, 1);    // line between points 1 and 2
line1->SetPointId(1, 2);
```

Cells are inserted in the mesh using the `SetCell()` method. It requires an identifier and the AutoPointer to the cell. The Mesh will take ownership of the cell to which the AutoPointer is pointing. This is done internally by the `SetCell()` method. In this way, the destruction of the CellAutoPointer will not induce the destruction of the associated cell.

```
mesh->SetCell(0, line0);
mesh->SetCell(1, line1);
```

After serving as an argument of the `SetCell()` method, a CellAutoPointer no longer holds ownership of the cell. It is important not to use this same CellAutoPointer again as argument to `SetCell()` without first securing ownership of another cell.

The number of Cells currently inserted in the mesh can be queried with the `GetNumberOfCells()` method.

```
std::cout << "Cells  = " << mesh->GetNumberOfCells()  << std::endl;
```

In a way analogous to points, cells can be accessed using Iterators to the CellsContainer in the mesh. The trait for the cell iterator can be extracted from the mesh and used to define a local type.

```
typedef MeshType::CellsContainer::Iterator CellIterator;
```

Then the iterators to the first and past-end cell in the mesh can be obtained respectively with the `Begin()` and `End()` methods of the CellsContainer. The CellsContainer of the mesh is returned by the `GetCells()` method.

```
CellIterator cellIterator = mesh->GetCells()->Begin();
CellIterator end          = mesh->GetCells()->End();
```

Finally a standard loop is used to iterate over all the cells. Note the use of the `Value()` method used to get the actual pointer to the cell from the CellIterator. Note also that the values returned are pointers to the generic CellType. These pointers have to be down-casted in order to be used as actual LineCell types. Safe down-casting is performed with the `dynamic_cast` operator which will throw an exception if the conversion cannot be safely performed.

```
while (cellIterator != end)
  {
```

```
  MeshType::CellType * cellptr = cellIterator.Value();
  LineType *           line = dynamic_cast<LineType *>(cellptr);
  std::cout << line->GetNumberOfPoints() << std::endl;
  ++cellIterator;
  }
```

5.3.3 Managing Data in Cells

The source code for this example can be found in the file
`Examples/DataRepresentation/Mesh/Mesh3.cxx`.

In the same way that custom data can be associated with points in the mesh, it is also possible to associate custom data with cells. The type of the data associated with the cells can be different from the data type associated with points. By default, however, these two types are the same. The following example illustrates how to access data associated with cells. The approach is analogous to the one used to access point data.

Consider the example of a mesh containing lines on which values are associated with each line. The mesh and cell header files should be included first.

```
#include "itkMesh.h"
#include "itkLineCell.h"
```

Then the PixelType is defined and the mesh type is instantiated with it.

```
typedef float                    PixelType;
typedef itk::Mesh<PixelType, 2> MeshType;
```

The `itk::LineCell` type can now be instantiated using the traits taken from the Mesh.

```
typedef MeshType::CellType      CellType;
typedef itk::LineCell<CellType> LineType;
```

Let's now create a Mesh and insert some points into it. Note that the dimension of the points matches the dimension of the Mesh. Here we insert a sequence of points that look like a plot of the log() function.

```
MeshType::Pointer mesh = MeshType::New();

typedef MeshType::PointType PointType;
PointType point;

const unsigned int numberOfPoints = 10;
for (unsigned int id = 0; id < numberOfPoints; id++)
  {
  point[0] = static_cast<PointType::ValueType>(id);   // x
  point[1] = log(static_cast<double>(id));            // y
  mesh->SetPoint(id, point);
  }
```

A set of line cells is created and associated with the existing points by using point identifiers. In this simple case, the point identifiers can be deduced from cell identifiers since the line cells are ordered in the same way.

```
CellType::CellAutoPointer line;
const unsigned int        numberOfCells = numberOfPoints - 1;
for (unsigned int cellId = 0; cellId < numberOfCells; cellId++)
  {
  line.TakeOwnership(new LineType);
  line->SetPointId(0, cellId);     // first point
  line->SetPointId(1, cellId + 1); // second point
  mesh->SetCell(cellId, line);     // insert the cell
  }
```

Data associated with cells is inserted in the `itk::Mesh` by using the `SetCellData()` method. It requires the user to provide an identifier and the value to be inserted. The identifier should match one of the inserted cells. In this simple example, the square of the cell identifier is used as cell data. Note the use of `static_cast` to `PixelType` in the assignment.

```
for (unsigned int cellId = 0; cellId < numberOfCells; cellId++)
  {
  mesh->SetCellData(cellId, static_cast<PixelType>(cellId * cellId));
  }
```

Cell data can be read from the Mesh with the `GetCellData()` method. It requires the user to provide the identifier of the cell for which the data is to be retrieved. The user should provide also a valid pointer to a location where the data can be copied.

```
for (unsigned int cellId = 0; cellId < numberOfCells; cellId++)
  {
  PixelType value = itk::NumericTraits<PixelType>::Zero;
  mesh->GetCellData(cellId, &value);
  std::cout << "Cell " << cellId << " = " << value << std::endl;
  }
```

Neither `SetCellData()` or `GetCellData()` are efficient ways to access cell data. More efficient access to cell data can be achieved by using the Iterators built into the `CellDataContainer`.

```
typedef MeshType::CellDataContainer::ConstIterator CellDataIterator;
```

Note that the `ConstIterator` is used here because the data is only going to be read. This approach is exactly the same already illustrated for getting access to point data. The iterator to the first cell data item can be obtained with the `Begin()` method of the CellDataContainer. The past-end iterator is returned by the `End()` method. The cell data container itself can be obtained from the mesh with the method `GetCellData()`.

```
CellDataIterator cellDataIterator  = mesh->GetCellData()->Begin();
CellDataIterator end               = mesh->GetCellData()->End();
```

Finally a standard loop is used to iterate over all the cell data entries. Note the use of the `Value()` method used to get the actual value of the data entry. `PixelType` elements are copied into the local variable `cellValue`.

```
while (cellDataIterator != end)
  {
  PixelType cellValue = cellDataIterator.Value();
  std::cout << cellValue << std::endl;
  ++cellDataIterator;
  }
```

More details about the use of `itk::Mesh` can be found in the ITK Software Guide.

5.4 Path

5.4.1 Creating a PolyLineParametricPath

The source code for this example can be found in the file `Examples/DataRepresentation/Path/PolyLineParametricPath1.cxx`.

This example illustrates how to use the `itk::PolyLineParametricPath`. This class will typically be used for representing in a concise way the output of an image segmentation algorithm in 2D. See section 14.3 for an example in the context of alignment detection. The `PolyLineParametricPath` however could also be used for representing any open or close curve in N-Dimensions as a linear piece-wise approximation.

First, the header file of the `PolyLineParametricPath` class must be included.

```
#include "itkPolyLineParametricPath.h"
```

The path is instantiated over the dimension of the image.

```
const unsigned int Dimension = 2;

typedef otb::Image<unsigned char, Dimension> ImageType;

typedef itk::PolyLineParametricPath<Dimension> PathType;
```

```
ImageType::ConstPointer image = reader->GetOutput();

PathType::Pointer path = PathType::New();

path->Initialize();

typedef PathType::ContinuousIndexType ContinuousIndexType;

ContinuousIndexType cindex;
```

```
typedef ImageType::PointType ImagePointType;

ImagePointType origin = image->GetOrigin();

ImageType::SpacingType spacing = image->GetSpacing();
ImageType::SizeType    size    = image->GetBufferedRegion().GetSize();

ImagePointType point;

point[0] = origin[0] + spacing[0] * size[0];
point[1] = origin[1] + spacing[1] * size[1];

image->TransformPhysicalPointToContinuousIndex(origin, cindex);

path->AddVertex(cindex);

image->TransformPhysicalPointToContinuousIndex(point, cindex);

path->AddVertex(cindex);
```

CHAPTER

SIX

READING AND WRITING IMAGES

This chapter describes the toolkit architecture supporting reading and writing of images to files. OTB does not enforce any particular file format, instead, it provides a structure inherited from ITK, supporting a variety of formats that can be easily extended by the user as new formats become available.

We begin the chapter with some simple examples of file I/O.

6.1 Basic Example

The source code for this example can be found in the file
`Examples/IO/ImageReadWrite.cxx`.

The classes responsible for reading and writing images are located at the beginning and end of the data processing pipeline. These classes are known as data sources (readers) and data sinks (writers). Generally speaking they are referred to as filters, although readers have no pipeline input and writers have no pipeline output.

The reading of images is managed by the class `otb::ImageFileReader` while writing is performed by the class `otb::ImageFileWriter`. These two classes are independent of any particular file format. The actual low level task of reading and writing specific file formats is done behind the scenes by a family of classes of type `itk::ImageIO`. Actually, the OTB image Readers and Writers are very similar to those of ITK, but provide new functionnalities which are specific to remote sensing images.

The first step for performing reading and writing is to include the following headers.

```
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
```

Then, as usual, a decision must be made about the type of pixel used to represent the image processed by the pipeline. Note that when reading and writing images, the pixel type of the image **is not**

necessarily the same as the pixel type stored in the file. Your choice of the pixel type (and hence template parameter) should be driven mainly by two considerations:

- It should be possible to cast the file pixel type in the file to the pixel type you select. This casting will be performed using the standard C-language rules, so you will have to make sure that the conversion does not result in information being lost.
- The pixel type in memory should be appropriate to the type of processing you intended to apply on the images.

A typical selection for remote sensing images is illustrated in the following lines.

```
typedef unsigned short PixelType;
const unsigned int Dimension = 2;
typedef otb::Image<PixelType, Dimension> ImageType;
```

Note that the dimension of the image in memory should match the one of the image in file. There are a couple of special cases in which this condition may be relaxed, but in general it is better to ensure that both dimensions match. This is not a real issue in remote sensing, unless you want to consider multi-band images as volumes (3D) of data.

We can now instantiate the types of the reader and writer. These two classes are parameterized over the image type.

```
typedef otb::ImageFileReader<ImageType> ReaderType;
typedef otb::ImageFileWriter<ImageType> WriterType;
```

Then, we create one object of each type using the New() method and assigning the result to a `itk::SmartPointer`.

```
ReaderType::Pointer reader = ReaderType::New();
WriterType::Pointer writer = WriterType::New();
```

The name of the file to be read or written is passed with the SetFileName() method.

```
reader->SetFileName(inputFilename);
writer->SetFileName(outputFilename);
```

We can now connect these readers and writers to filters to create a pipeline. For example, we can create a short pipeline by passing the output of the reader directly to the input of the writer.

```
writer->SetInput(reader->GetOutput());
```

At first view, this may seem as a quite useless program, but it is actually implementing a powerful file format conversion tool! The execution of the pipeline is triggered by the invocation of the `Update()` methods in one of the final objects. In this case, the final data pipeline object is the writer. It is a wise practice of defensive programming to insert any `Update()` call inside a `try/catch` block in case exceptions are thrown during the execution of the pipeline.

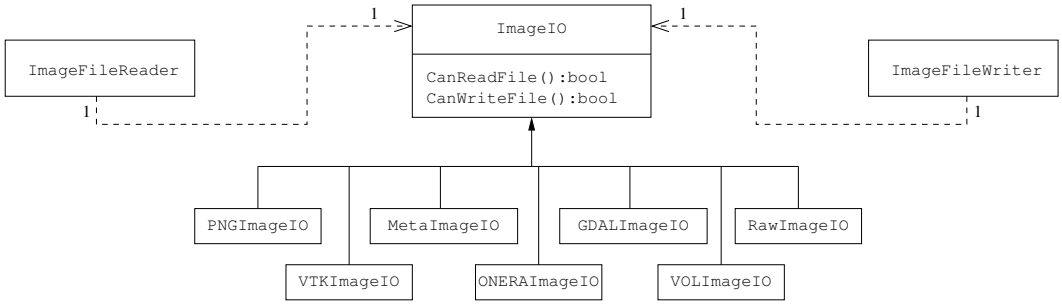


Figure 6.1: Collaboration diagram of the ImageIO classes.

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& err)
  {
  std::cerr << "ExceptionObject caught !" << std::endl;
  std::cerr << err << std::endl;
  return EXIT_FAILURE;
  }
```

Note that exceptions should only be caught by pieces of code that know what to do with them. In a typical application this `catch` block should probably reside on the GUI code. The action on the `catch` block could inform the user about the failure of the IO operation.

The IO architecture of the toolkit makes it possible to avoid explicit specification of the file format used to read or write images.[1] The object factory mechanism enables the ImageFileReader and ImageFileWriter to determine (at run-time) with which file format it is working with. Typically, file formats are chosen based on the filename extension, but the architecture supports arbitrarily complex processes to determine whether a file can be read or written. Alternatively, the user can specify the data file format by explicit instantiation and assignment the appropriate `itk::ImageIO` subclass.

To better understand the IO architecture, please refer to Figures 6.1, 6.2, and 6.3.

The following section describes the internals of the IO architecture provided in the toolbox.

6.2 Pluggable Factories

The principle behind the input/output mechanism used in ITK and therefore OTB is known as *pluggable-factories* [48]. This concept is illustrated in the UML diagram in Figure 6.1.

[1] In this example no file format is specified; this program can be used as a general file conversion utility.

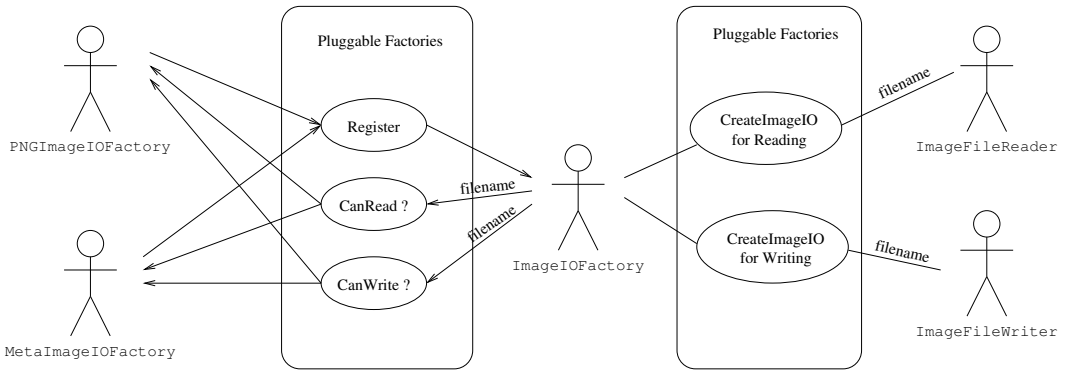


Figure 6.2: Use cases of ImageIO factories.

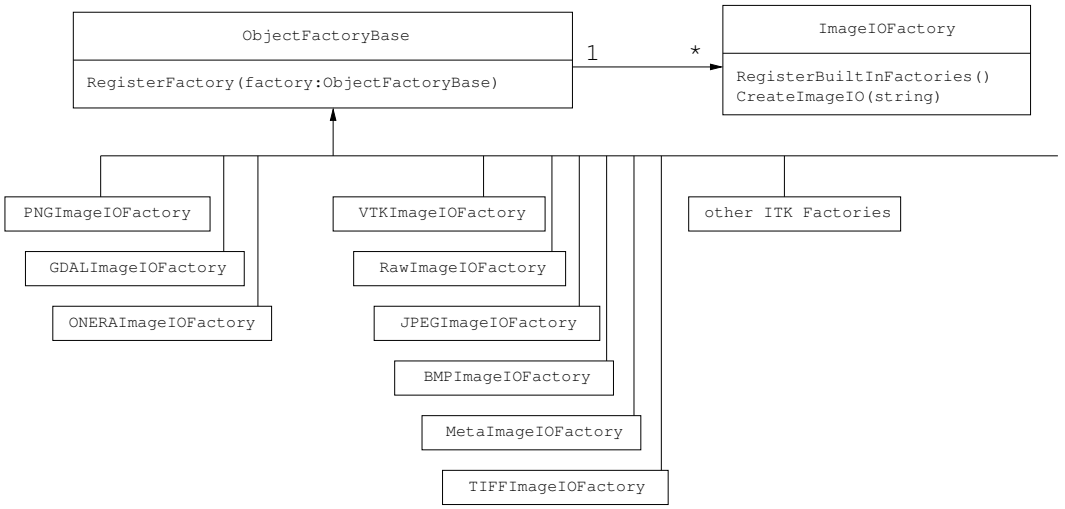


Figure 6.3: Class diagram of the ImageIO factories.

From the user's point of view the objects responsible for reading and writing files are the `otb::ImageFileReader` and `otb::ImageFileWriter` classes. These two classes, however, are not aware of the details involved in reading or writing particular file formats like PNG or GeoTIFF. What they do is to dispatch the user's requests to a set of specific classes that are aware of the details of image file formats. These classes are the `itk::ImageIO` classes. The ITK delegation mechanism enables users to extend the number of supported file formats by just adding new classes to the ImageIO hierarchy.

Each instance of ImageFileReader and ImageFileWriter has a pointer to an ImageIO object. If this pointer is empty, it will be impossible to read or write an image and the image file reader/writer must determine which ImageIO class to use to perform IO operations. This is done basically by passing the filename to a centralized class, the `itk::ImageIOFactory` and asking it to identify any subclass of ImageIO capable of reading or writing the user-specified file. This is illustrated by the use cases on the right side of Figure 6.2. The ImageIOFactory acts here as a dispatcher that help to locate the actual IO factory classes corresponding to each file format.

Each class derived from ImageIO must provide an associated factory class capable of producing an instance of the ImageIO class. For example, for PNG files, there is a `itk::PNGImageIO` object that knows how to read this image files and there is a `itk::PNGImageIOFactory` class capable of constructing a PNGImageIO object and returning a pointer to it. Each time a new file format is added (i.e., a new ImageIO subclass is created), a factory must be implemented as a derived class of the ObjectFactoryBase class as illustrated in Figure 6.3.

For example, in order to read PNG files, a PNGImageIOFactory is created and registered with the central ImageIOFactory singleton[2] class as illustrated in the left side of Figure 6.2. When the ImageFileReader asks the ImageIOFactory for an ImageIO capable of reading the file identified with *filename* the ImageIOFactory will iterate over the list of registered factories and will ask each one of them is they know how to read the file. The factory that responds affirmatively will be used to create the specific ImageIO instance that will be returned to the ImageFileReader and used to perform the read operations.

With respect to the ITK formats, OTB adds most of the remote sensing image formats. In order to do so, the Geospatial Data Abstraction Library, GDAL `http://www.gdal.org/`, is encapsultated in a ImageIO factory. GDAL is a translator library for raster geospatial data formats that is released under an X/MIT style Open Source license. As a library, it presents a single abstract data model to the calling application for all supported formats, which include CEOS, GeoTIFF, ENVI, and much more. See `http://www.gdal.org/formats_list.html` for the full format list.

Since GDAL is itself a multi-format library, the GDAL IO factory is able to choose the appropriate ressource for reading and writing images.

In most cases the mechanism is transparent to the user who only interacts with the ImageFileReader and ImageFileWriter. It is possible, however, to explicitly select the type of ImageIO object to use. Please see the ITK Software for more details about this.

[2] *Singleton* means that there is only one instance of this class in a particular application

6.3 IO Streaming

6.3.1 Implicit Streaming

The source code for this example can be found in the file
`Examples/IO/StreamingImageReadWrite.cxx`.

As we have seen, the reading of images is managed by the class `otb::ImageFileReader` while writing is performed by the class `otb::ImageFileWriter`. ITK's pipeline implements streaming. That means that a filter for which the `ThreadedGenerateData` method is implemented, will only produce the data for the region requested by the following filter in the pipeline. Therefore, in order to use the streaming functionnality one needs to use a filter at the end of the pipeline which requests for adjacent regions of the image to be processed. In ITK, the `itk::StreamingImageFilter` class is used for this purpose. However, ITK does not implement streaming from/to files. This means that even if the pipeline has a small memory footprint, the images have to be stored in memory at least after the read operation and before the write operation.

OTB implements read/write streaming. For the image file reading, this is transparent for the programmer, and if a streaming loop is used at the end of the pipeline, the read operation will be streamed. For the file writing, the `otb::ImageFileWriter` has to be used.

The first step for performing streamed reading and writing is to include the following headers.

```
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
```

Then, as usual, a decision must be made about the type of pixel used to represent the image processed by the pipeline.

```
  typedef unsigned char PixelType;
  const unsigned int Dimension = 2;
  typedef otb::Image<PixelType, Dimension> ImageType;
```

We can now instantiate the types of the reader and writer. These two classes are parameterized over the image type. We will rescale the intensities of the as an example of intermediate processing step.

```
  typedef otb::ImageFileReader<ImageType>                          ReaderType;
  typedef itk::RescaleIntensityImageFilter<ImageType, ImageType> RescalerType;
  typedef otb::ImageFileWriter<ImageType>                 WriterType;
```

Then, we create one object of each type using the New() method and assigning the result to a `itk::SmartPointer`.

```
  ReaderType::Pointer   reader = ReaderType::New();
  RescalerType::Pointer rescaler = RescalerType::New();
  WriterType::Pointer   writer = WriterType::New();
```

The name of the file to be read or written is passed with the SetFileName() method. We also choose the range of intensities for the rescaler.

```
reader->SetFileName(inputFilename);
rescaler->SetOutputMinimum(0);
rescaler->SetOutputMaximum(255);
writer->SetFileName(outputFilename);
```

We can now connect these readers and writers to filters to create a pipeline.

```
rescaler->SetInput(reader->GetOutput());
writer->SetInput(rescaler->GetOutput());
```

We can now trigger the pipeline execution by calling the `Update` method on the writer.

```
  writer->Update();
```

The writer will ask its preceding filter to provide different portions of the image. Each filter in the pipeline will do the same until the request arrives to the reader. In this way, the pipeline will be executed for each requested region and the whole input image will be read, processed and written without being fully loaded in memory.

6.3.2 Explicit Streaming

The source code for this example can be found in the file `Examples/IO/ExplicitStreamingExample.cxx`.

Usually, the streaming process is hidden within the pipeline. This allows the user to get rid of the annoying task of splitting the images into tiles, and so on. However, for some kinds of processing, we do not really need a pipeline: no writer is needed, only read access to pixel values is wanted. In these cases, one has to explicitly set up the streaming procedure. Fortunately, OTB offers a high level of abstraction for this task. We will need to include the following header files:

```
#include "itkImageRegionSplitter.h"
#include "otbStreamingTraits.h"
```

The `otb::StreamingTraits` class manages the streaming approaches which are possible with the image type over which it is templated. The class `itk::ImageRegionSplitter` is templated over the number of dimensions of the image and will perform the actual image splitting. More information on splitter can be found in section 27.3

```
typedef otb::StreamingTraits<ImageType> StreamingTraitsType;
typedef itk::ImageRegionSplitter<2>     SplitterType;
```

Once a region of the image is available, we will use classical region iterators to get the pixels.

```
typedef ImageType::RegionType RegionType;

typedef itk::ImageRegionConstIterator<ImageType> IteratorType;
```

We instantiate the image file reader, but in order to avoid reading the whole image, we call the `GenerateOutputInformation()` method instead of the `Update()` one. `GenerateOutputInformation()` will make available the information about sizes, band, resolutions, etc. After that, we can access the largest possible region of the input image.

```
ImageReaderType::Pointer reader = ImageReaderType::New();

reader->SetFileName(infname);

reader->GenerateOutputInformation();

RegionType largestRegion = reader->GetOutput()->GetLargestPossibleRegion();
```

We set up now the local streaming capabilities by asking the streaming traits to compute the number of regions to split the image into given the splitter, the user defined number of lines, and the input image information.

```
SplitterType::Pointer splitter = SplitterType::New();
unsigned int          numberOfStreamDivisions =
  StreamingTraitsType::CalculateNumberOfStreamDivisions(
    reader->GetOutput(),
    largestRegion,
    splitter,
    otb::SET_BUFFER_NUMBER_OF_LINES,
    0, 0, nbLinesForStreaming);
```

We can now get the split regions and iterate through them.

```
unsigned int piece = 0;
RegionType   streamingRegion;

for (piece = 0;
     piece < numberOfStreamDivisions;
     piece++)
  {
```

We get the region

```
  streamingRegion =
    splitter->GetSplit(piece, numberOfStreamDivisions, largestRegion);

  std::cout << "Processing region: " << streamingRegion << std::endl;
```

We ask the reader to provide the region.

```
  reader->GetOutput()->SetRequestedRegion(streamingRegion);
  reader->GetOutput()->PropagateRequestedRegion();
  reader->GetOutput()->UpdateOutputData();
```

We declare an iterator and walk through the region.

```
  IteratorType it(reader->GetOutput(), streamingRegion);
  it.GoToBegin();

  while (!it.IsAtEnd())
    {
    std::cout << it.Get() << std::endl;
    ++it;
    }
```

6.4 Reading and Writing RGB Images

The source code for this example can be found in the file `Examples/IO/RGBImageReadWrite.cxx`.

RGB images are commonly used for representing data acquired from multispectral sensors. This example illustrates how to read and write RGB color images to and from a file. This requires the following headers as shown.

```
#include "itkRGBPixel.h"
#include "otbImage.h"
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
```

The `itk::RGBPixel` class is templated over the type used to represent each one of the red, green and blue components. A typical instantiation of the RGB image class might be as follows.

```
typedef itk::RGBPixel<unsigned char> PixelType;
typedef otb::Image<PixelType, 2>     ImageType;
```

The image type is used as a template parameter to instantiate the reader and writer.

```
typedef otb::ImageFileReader<ImageType> ReaderType;
typedef otb::ImageFileWriter<ImageType> WriterType;

ReaderType::Pointer reader = ReaderType::New();
WriterType::Pointer writer = WriterType::New();
```

The filenames of the input and output files must be provided to the reader and writer respectively.

```
reader->SetFileName(inputFilename);
writer->SetFileName(outputFilename);
```

Finally, execution of the pipeline can be triggered by invoking the `Update()` method in the writer.

```
writer->Update();
```

You may have noticed that apart from the declaration of the `PixelType` there is nothing in this code that is specific for RGB images. All the actions required to support color images are implemented internally in the `itk::ImageIO` objects.

6.5 Reading, Casting and Writing Images

The source code for this example can be found in the file
`Examples/IO/ImageReadCastWrite.cxx`.

Given that ITK and OTB are based on the Generic Programming paradigm, most of the types are defined at compilation time. It is sometimes important to anticipate conversion between different types of images. The following example illustrates the common case of reading an image of one pixel type and writing it on a different pixel type. This process not only involves casting but also rescaling the image intensity since the dynamic range of the input and output pixel types can be quite different. The `itk::RescaleIntensityImageFilter` is used here to linearly rescale the image values.

The first step in this example is to include the appropriate headers.

```
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
#include "itkRescaleIntensityImageFilter.h"
```

Then, as usual, a decision should be made about the pixel type that should be used to represent the images. Note that when reading an image, this pixel type **is not necessarily** the pixel type of the image stored in the file. Instead, it is the type that will be used to store the image as soon as it is read into memory.

```
  typedef float         InputPixelType;
  typedef unsigned char OutputPixelType;
  const unsigned int Dimension = 2;

  typedef otb::Image<InputPixelType,  Dimension> InputImageType;
  typedef otb::Image<OutputPixelType, Dimension> OutputImageType;
```

We can now instantiate the types of the reader and writer. These two classes are parameterized over the image type.

```
  typedef otb::ImageFileReader<InputImageType>  ReaderType;
  typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

Below we instantiate the RescaleIntensityImageFilter class that will linearly scale the image intensities.

```
  typedef itk::RescaleIntensityImageFilter<
      InputImageType,
      OutputImageType>    FilterType;
```

A filter object is constructed and the minimum and maximum values of the output are selected using the SetOutputMinimum() and SetOutputMaximum() methods.

```
FilterType::Pointer filter = FilterType::New();
filter->SetOutputMinimum(0);
filter->SetOutputMaximum(255);
```

Then, we create the reader and writer and connect the pipeline.

```
ReaderType::Pointer reader = ReaderType::New();
WriterType::Pointer writer = WriterType::New();

filter->SetInput(reader->GetOutput());
writer->SetInput(filter->GetOutput());
```

The name of the files to be read and written are passed with the SetFileName() method.

```
reader->SetFileName(inputFilename);
writer->SetFileName(outputFilename);
```

Finally we trigger the execution of the pipeline with the Update() method on the writer. The output image will then be the scaled and cast version of the input image.

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& err)
  {
  std::cerr << "ExceptionObject caught !" << std::endl;
  std::cerr << err << std::endl;
  return EXIT_FAILURE;
  }
```

6.6 Extracting Regions

The source code for this example can be found in the file
`Examples/IO/ImageReadRegionOfInterestWrite.cxx`.

This example should arguably be placed in the filtering chapter. However its usefulness for typical IO operations makes it interesting to mention here. The purpose of this example is to read and image, extract a subregion and write this subregion to a file. This is a common task when we want to apply a computationally intensive method to the region of interest of an image.

As usual with OTB IO, we begin by including the appropriate header files.

```
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
```

The otb::ExtractROI is the filter used to extract a region from an image. Its header is included below.

```
#include "otbExtractROI.h"
```

Image types are defined below.

```
typedef unsigned char InputPixelType;
typedef unsigned char OutputPixelType;
const unsigned int Dimension = 2;
typedef otb::Image<InputPixelType,  Dimension> InputImageType;
typedef otb::Image<OutputPixelType, Dimension> OutputImageType;
```

The types for the otb::ImageFileReader and otb::ImageFileWriter are instantiated using the image types.

```
typedef otb::ImageFileReader<InputImageType>  ReaderType;
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

The ExtractROI type is instantiated using the input and output pixel types. Using the pixel types as template parameters instead of the image types allows to restrict the use of this class to otb::Images which are used with scalar pixel types. See section 6.8.1 for the extraction of ROIs on otb::VectorImages. A filter object is created with the New() method and assigned to a itk::SmartPointer.

```
typedef otb::ExtractROI<InputImageType::PixelType,
    OutputImageType::PixelType> FilterType;

FilterType::Pointer filter = FilterType::New();
```

The ExtractROI requires a region to be defined by the user. This is done by defining a rectangle with the following methods (the filter assumes that a 2D image is being processed, for N-D region extraction, you can use the itk::RegionOfInterestImageFilter class).

```
filter->SetStartX(atoi(argv[3]));
filter->SetStartY(atoi(argv[4]));
filter->SetSizeX(atoi(argv[5]));
filter->SetSizeY(atoi(argv[6]));
```

Below, we create the reader and writer using the New() method and assigning the result to a SmartPointer.

```
ReaderType::Pointer reader = ReaderType::New();
WriterType::Pointer writer = WriterType::New();
```

The name of the file to be read or written is passed with the SetFileName() method.

```
reader->SetFileName(inputFilename);
writer->SetFileName(outputFilename);
```

Below we connect the reader, filter and writer to form the data processing pipeline.

```
filter->SetInput(reader->GetOutput());
writer->SetInput(filter->GetOutput());
```

Finally we execute the pipeline by invoking Update() on the writer. The call is placed in a `try/catch` block in case exceptions are thrown.

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& err)
  {
  std::cerr << "ExceptionObject caught !" << std::endl;
  std::cerr << err << std::endl;
  return EXIT_FAILURE;
  }
```

6.7 Reading and Writing Vector Images

Images whose pixel type is a Vector, a CovariantVector, an Array, or a Complex are quite common in image processing. One of the uses of these tye of images is the processing of SLC SAR images, which are complex.

6.7.1 Reading and Writing Complex Images

The source code for this example can be found in the file
`Examples/IO/ComplexImageReadWrite.cxx`.

This example illustrates how to read and write an image of pixel type `std::complex`. The complex type is defined as an integral part of the C++ language.

We start by including the headers of the complex class, the image, and the reader and writer classes.

```
#include <complex>
#include "otbImage.h"
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
```

The image dimension and pixel type must be declared. In this case we use the `std::complex<>` as the pixel type. Using the dimension and pixel type we proceed to instantiate the image type.

```
const unsigned int Dimension = 2;

typedef std::complex<float>              PixelType;
typedef otb::Image<PixelType, Dimension> ImageType;
```

The image file reader and writer types are instantiated using the image type. We can then create objects for both of them.

```
typedef otb::ImageFileReader<ImageType> ReaderType;
typedef otb::ImageFileWriter<ImageType> WriterType;

ReaderType::Pointer reader = ReaderType::New();
WriterType::Pointer writer = WriterType::New();
```

Filenames should be provided for both the reader and the writer. In this particular example we take those filenames from the command line arguments.

```
reader->SetFileName(argv[1]);
writer->SetFileName(argv[2]);
```

Here we simply connect the output of the reader as input to the writer. This simple program could be used for converting complex images from one fileformat to another.

```
writer->SetInput(reader->GetOutput());
```

The execution of this short pipeline is triggered by invoking the Update() method of the writer. This invocation must be placed inside a try/catch block since its execution may result in exceptions being thrown.

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& err)
  {
  std::cerr << "ExceptionObject caught !" << std::endl;
  std::cerr << err << std::endl;
  return EXIT_FAILURE;
  }
```

For a more interesting use of this code, you may want to add a filter in between the reader and the writer and perform any complex image to complex image operation.

6.8 Reading and Writing Multiband Images

The source code for this example can be found in the file
`Examples/IO/MultibandImageReadWrite.cxx`.

The `otb::Image` class with a vector pixel type could be used for representing multispectral images, with one band per vector component, however, this is not a practical way, since the dimensionality of the vector must be known at compile time. OTB offers the `otb::VectorImage` where the dimensionality of the vector stored for each pixel can be chosen at runtime. This is needed for the image file readers in order to dynamically set the number of bands of an image read from a file.

The OTB Readers and Writers are able to deal with `otb::VectorImage`s transparently for the user.

The first step for performing reading and writing is to include the following headers.

```
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
```

Then, as usual, a decision must be made about the type of pixel used to represent the image processed by the pipeline. The pixel type corresponds to the scalar type stored in the vector components. Therefore, for a multiband Pléiades image we will do:

```
typedef unsigned short PixelType;
const unsigned int Dimension = 2;
typedef otb::VectorImage<PixelType, Dimension> ImageType;
```

We can now instantiate the types of the reader and writer. These two classes are parameterized over the image type.

```
typedef otb::ImageFileReader<ImageType> ReaderType;
typedef otb::ImageFileWriter<ImageType> WriterType;
```

Then, we create one object of each type using the New() method and assigning the result to a `itk::SmartPointer`.

```
ReaderType::Pointer reader = ReaderType::New();
WriterType::Pointer writer = WriterType::New();
```

The name of the file to be read or written is passed with the SetFileName() method.

```
reader->SetFileName(inputFilename);
writer->SetFileName(outputFilename);
```

We can now connect these readers and writers to filters to create a pipeline. The only thig to take care of is, when executing the program, choosing an output image file format which supports multiband images.

```
writer->SetInput(reader->GetOutput());
```

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& err)
  {
  std::cerr << "ExceptionObject caught !" << std::endl;
  std::cerr << err << std::endl;
  return EXIT_FAILURE;
  }
```

6.8.1 Extracting ROIs

The source code for this example can be found in the file
`Examples/IO/ExtractROI.cxx`.

This example shows the use of the `otb::MultiChannelExtractROI` and `otb::MultiToMonoChannelExtractROI` which allow the extraction of ROIs from multiband images stored into `otb::VectorImage`s. The first one povides a Vector Image as output, while the second one provides a classical `otb::Image` with a scalar pixel type. The present example shows how to extract a ROI from a 4-band SPOT 5 image and to produce a first multi-band 3-channel image and a second mono-channel one for the SWIR band.

We start by including the needed header files.

```
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
#include "otbMultiChannelExtractROI.h"
#include "otbMultiToMonoChannelExtractROI.h"
```

The program arguments define the image file names as well as the rectangular area to be extracted.

```
  const char * inputFilename  = argv[1];
  const char * outputFilenameRGB = argv[2];
  const char * outputFilenameMIR = argv[3];

  unsigned int startX((unsigned int) ::atoi(argv[4]));
  unsigned int startY((unsigned int) ::atoi(argv[5]));
  unsigned int sizeX((unsigned int) ::atoi(argv[6]));
  unsigned int sizeY((unsigned int) ::atoi(argv[7]));
```

As usual, we define the input and output pixel types.

```
  typedef   unsigned char InputPixelType;
  typedef   unsigned char OutputPixelType;
```

First of all, we extract the multiband part by using the `otb::MultiChannelExtractROI` class, which is templated over the input and output pixel types. This class in not templated over the images types in order to force these images to be of `otb::VectorImage` type.

```
  typedef otb::MultiChannelExtractROI<InputPixelType,
      OutputPixelType>  ExtractROIFilterType;
```

We create the extractor filter by using the `New` method of the class and we set its parameters.

```
  ExtractROIFilterType::Pointer extractROIFilter = ExtractROIFilterType::New();

  extractROIFilter->SetStartX(startX);
  extractROIFilter->SetStartY(startY);
  extractROIFilter->SetSizeX(sizeX);
  extractROIFilter->SetSizeY(sizeY);
```

We must tell the filter which are the channels to be used. When selecting contiguous bands, we can use the `SetFirstChannel` and the `SetLastChannel`. Otherwise, we select individual channels by using the `SetChannel` method.

```
extractROIFilter->SetFirstChannel(1);
extractROIFilter->SetLastChannel(3);
```

We will use the OTB readers and writers for file access.

```
typedef otb::ImageFileReader<ExtractROIFilterType::InputImageType> ReaderType;
typedef otb::ImageFileWriter<ExtractROIFilterType::InputImageType> WriterType;

ReaderType::Pointer reader = ReaderType::New();
WriterType::Pointer writer = WriterType::New();
```

Since the number of bands of the input image is dynamically set at runtime, the `UpdateOutputInformation` method of the reader must be called before using the extractor filter.

```
reader->SetFileName(inputFilename);
reader->UpdateOutputInformation();
writer->SetFileName(outputFilenameRGB);
```

We can then build the pipeline as usual.

```
extractROIFilter->SetInput(reader->GetOutput());

writer->SetInput(extractROIFilter->GetOutput());
```

And execute the pipeline by calling the `Update` method of the writer.

```
writer->Update();
```

The usage of the `otb::MultiToMonoChannelExtractROI` is similar to the one of the `otb::MultiChannelExtractROI` described above.

The goal now is to extract an ROI from a multi-band image and generate a mono-channel image as output.

We could use the `otb::MultiChannelExtractROI` and select a single channel, but using the `otb::MultiToMonoChannelExtractROI` we generate a `otb::Image` instead of an `otb::VectorImage`. This is useful from a computing and memory usage point of view. This class is also templated over the pixel types.

```
typedef otb::MultiToMonoChannelExtractROI<InputPixelType,
    OutputPixelType>
ExtractROIMonoFilterType;
```

For this filter, only one output channel has to be selected.

```
extractROIMonoFilter->SetChannel(4);
```

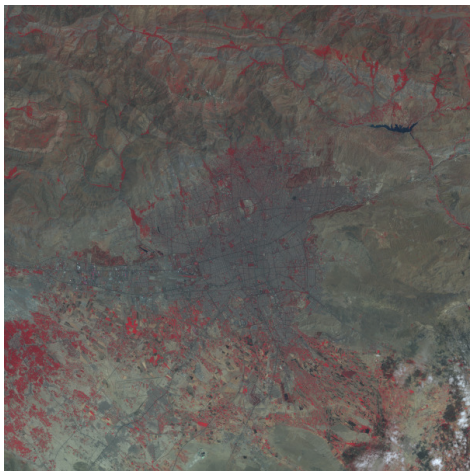


Figure 6.4: Quicklook of the original SPOT 5 image.

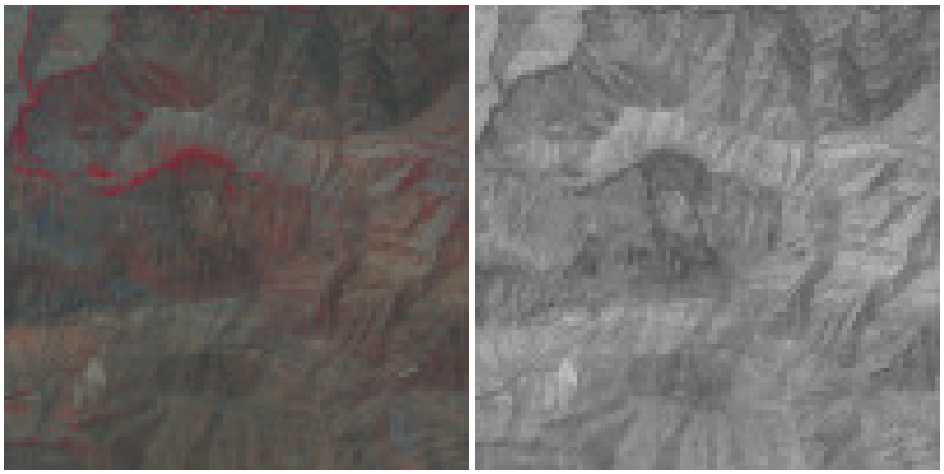


Figure 6.5: Result of the extraction. Left: 3-channel image. Right: mono-band image.

Figure 6.5 illustrates the result of the application of both extraction filters on the image presented in figure 6.4.

6.9 Reading Image Series

The source code for this example can be found in the file
`Examples/IO/ImageSeriesIOExample.cxx`.

This example shows how to read a list of images and concatenate them into a vector image. We will write a program which is able to perform this operation taking advantage of the streaming functionnalities of the processing pipeline. We will assume that all the input images have the same size and a single band.

The following header files will be needed:

```
#include "otbImage.h"
#include "otbVectorImage.h"
#include "otbImageFileReader.h"
#include "otbObjectList.h"
#include "otbImageList.h"
#include "otbImageListToVectorImageFilter.h"
#include "otbImageFileWriter.h"
```

We will start by defining the types for the input images and the associated readers.

```
typedef unsigned short int PixelType;
const unsigned int Dimension = 2;

typedef otb::Image<PixelType, Dimension> InputImageType;

typedef otb::ImageFileReader<InputImageType> ImageReaderType;
```

We will use a list of image file readers in order to open all the input images at once. For this, we use the `otb::ObjectList` object and we template it over the type of the readers.

```
typedef otb::ObjectList<ImageReaderType> ReaderListType;

ReaderListType::Pointer readerList = ReaderListType::New();
```

We will also build a list of input images in order to store the smart pointers obtained at the output of each reader. This allows us to build a pipeline without really reading the images and using lots of RAM. The `otb::ImageList` object will be used.

```
typedef otb::ImageList<InputImageType> ImageListType;

ImageListType::Pointer imageList = ImageListType::New();
```

We can now loop over the input image list in order to populate the reader list and the input image list.

```
for (unsigned int i = 0; i < NbImages; ++i)
  {

  ImageReaderType::Pointer imageReader = ImageReaderType::New();

  imageReader->SetFileName(argv[i + 2]);

  std::cout << "Adding image " << argv[i + 2] << std::endl;

  imageReader->UpdateOutputInformation();

  imageList->PushBack(imageReader->GetOutput());

  readerList->PushBack(imageReader);

  }
```

All the input images will be concatenated into a single output vector image. For this matter, we will use the `otb::ImageListToVectorImageFilter` which is templated over the input image list type and the output vector image type.

```
typedef otb::VectorImage<PixelType, Dimension> VectorImageType;

typedef otb::ImageListToVectorImageFilter<ImageListType, VectorImageType>
ImageListToVectorImageFilterType;

ImageListToVectorImageFilterType::Pointer iL2VI =
  ImageListToVectorImageFilterType::New();
```

We plug the image list as input of the filter and use a `otb::ImageFileWriter` to write the result image to a file, so that the streaming capabilities of all the readers and the filter are used.

```
iL2VI->SetInput(imageList);

typedef otb::ImageFileWriter<VectorImageType> ImageWriterType;

ImageWriterType::Pointer imageWriter = ImageWriterType::New();

imageWriter->SetFileName(argv[1]);
```

We can tune the size of the image tiles, so that the total memory footprint of the pipeline is constant for any execution of the program.

```
unsigned long memoryConsumptionInMB = 10;

std::cout << "Memory consumption: " << memoryConsumptionInMB << std::endl;

imageWriter->SetAutomaticTiledStreaming(memoryConsumptionInMB);

imageWriter->SetInput(iL2VI->GetOutput());

imageWriter->Update();
```

6.10 Extended filename for reader and writer

6.10.1 Syntax

The reader and writer extended file name support is based on the same syntax, only the options are different. To benefit from the extended file name mecanism, the following syntax is to be used:

```
Path/Image.ext?&key1=<value1>&key2=<value2>
```

IMPORTANT: Note that you'll probably need to "quote" the filename.

6.10.2 Reader options

Available Options:

- `&geom=<path/filename.geom>`
  - Contains the file name of a valid geom file
  - Use the content of the specified geom file instead of image-embedded geometric information
  - empty by default, use the image-embedded information if available
- `&sdataidx=<(int)idx>`
  - Select the sub-dataset to read
  - 0 by default
- `&resol=<(int)resolution factor>`
  - Select the JPEG2000 sub-resolution image to read
  - 0 by default
- `&skipcarto=<(bool)true>`
  - Skip the cartographic information
  - Clears the projectionref, set the origin to $[0,0]$ and the spacing to $[1/max(1,resolutionfactor),1/max(1,resolutionfactor)]$
  - Keeps the keyword list
  - false by default
- `&skipgeom=<(bool)true>`

  - Skip geometric information
  - Clears the keyword list
  - Keeps the projectionref and the origin/spacing informations
  - false by default.

6.10.3 Writer options

Available Options:

- `&writegeom=<(bool)false>`
  - To activate writing of external geom file
  - true by default
- `&gdal:co:<GDALKEY>=<VALUE>`
  - To specify a gdal creation option
  - For gdal creation option information, see dedicated gdal documentation
  - None by default
- `&streaming:type=<VALUE>`
  - Activates configuration of streaming through extended filenames
  - Override any previous configuration of streaming
  - Allows to configure the kind of streaming to perform
  - Available values are:
    * auto : tiled or stripped streaming mode chosen automatically depending on TileHint read from input files
    * tiled : tiled streaming mode
    * stripped : stripped streaming mode
    * none : explicitly deactivate streaming
  - Not set by default
- `&streaming:sizemode=<VALUE>`
  - Allows to choose how the size of the streaming pieces is computed
  - Available values are:
    * auto : size is estimated from the available memory setting by evaluating pipeline memory print

    - height : size is set by setting height of strips or tiles
    - nbsplits : size is computed from a given number of splits
  - Default is auto

- `&streaming:sizevalue=<VALUE>`
  - Parameter for size of streaming pieces computation
  - Value is :
    - if sizemode=auto : available memory in Mb
    - if sizemode=height : height of the strip or tile in pixels
    - if sizemode=nbsplits : number of requested splits for streaming
  - If not provided, the default value is set to 0 and result in different behaviour depending on sizemode (if set to height or nbsplits, streaming is deactivated, if set to auto, value is fetched from configuration or cmake configuration file)

- `&box=<startx>:<starty>:<sizex>:<sizey>`
  - User defined parameters of output image region
  - The region must be set with 4 unsigned integers (the separator used is the colon ':'). Values are:
    - startx: first index on X
    - starty: first index on Y
    - sizex: size along X
    - sizey: size along Y
  - The definition of the region follows the same convention as itk::Region definition in C++. A region is defined by two classes: the itk::Index and itk::Size classes. The origin of the region within the image with which it is associated is defined by Index

The available syntax for boolean options are:

- ON, On, on, true, True, 1 are available for setting a 'true' boolean value
- OFF, Off, off, false, False, 0 are available for setting a 'false' boolean value

CHAPTER

SEVEN

READING AND WRITING AUXILARY DATA

As we have seen in the previous chapter, OTB has a great capability to read and process images. However, images are not the only type of data we will need to manipulate. Images are characterized by a regular sampling grid. For some data, such as Digital Elevation Models (DEM) or Lidar, this is too restrictive and we need other representations.

Vector data are also used to represent cartographic objects, segmentation results, etc: basically, everything which can be seen as points, lines or polygons. OTB provides functionnalities for accessing this kind of data.

7.1 Reading DEM Files

The source code for this example can be found in the file `Examples/IO/DEMToImageGenerator.cxx`.

The following example illustrates the use of the `otb::DEMToImageGenerator` class. The aim of this class is to generate an image from the srtm data (precising the start extraction latitude and longitude point). Each pixel is a geographic point and its intensity is the altitude of the point. If srtm doesn't have altitude information for a point, the altitude value is set at -32768 (value of the srtm norm).

Let's look at the minimal code required to use this algorithm. First, the following header defining the `otb::DEMToImageGenerator` class must be included.

```
#include "otbDEMToImageGenerator.h"
```

The image type is now defined using pixel type and dimension. The output image is defined as an `otb::Image`.

```
const unsigned int Dimension = 2;
typedef otb::Image<double, Dimension> ImageType;
```

The DEMToImageGenerator is defined using the image pixel type as a template parameter. After that, the object can be instancied.

```
typedef otb::DEMToImageGenerator<ImageType> DEMToImageGeneratorType;

DEMToImageGeneratorType::Pointer object = DEMToImageGeneratorType::New();
```

Input parameter types are defined to set the value in the `otb::DEMToImageGenerator`.

```
typedef DEMToImageGeneratorType::SizeType       SizeType;
typedef DEMToImageGeneratorType::SpacingType    SpacingType;
typedef DEMToImageGeneratorType::PointType      PointType;
```

The path to the DEM folder is given to the `otb::DEMHandler`.

```
otb::DEMHandler::Instance()->OpenDEMDirectory(folderPath);
```

The origin (Longitude/Latitude) of the output image in the DEM is given to the filter.

```
PointType origin;
origin[0] = ::atof(argv[3]);
origin[1] = ::atof(argv[4]);

object->SetOutputOrigin(origin);
```

The size (in Pixel) of the output image is given to the filter.

```
SizeType size;
size[0] = ::atoi(argv[5]);
size[1] = ::atoi(argv[6]);

object->SetOutputSize(size);
```

The spacing (step between to consecutive pixel) is given to the filter. By default, this spacing is set at 0.001.

```
SpacingType spacing;
spacing[0] = ::atof(argv[7]);
spacing[1] = ::atof(argv[8]);

object->SetOutputSpacing(spacing);
```

The output image name is given to the writer and the filter output is linked to the writer input.

```
writer->SetFileName(outputName);

writer->SetInput(object->GetOutput());
```

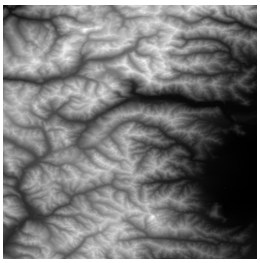


Figure 7.1: DEMToImageGenerator image.

The invocation of the `Update()` method on the writer triggers the execution of the pipeline. It is recommended to place update calls in a `try/catch` block in case errors occur and exceptions are thrown.

```
try
  {
  writer->Update();
  }

catch (itk::ExceptionObject& err)
  {
  std::cout << "Exception itk::ExceptionObject thrown !" << std::endl;
  std::cout << err << std::endl;
  return EXIT_FAILURE;
  }
```

Let's now run this example using as input the SRTM data contained in `DEM_srtm` folder. Figure 7.1 shows the obtained DEM. Invalid data values – hidden areas due to SAR shadowing – are set to zero.

7.2 Elevation management with OTB

The source code for this example can be found in the file `Examples/IO/DEMHandlerExample.cxx`.

OTB relies on OSSIM for elevation handling. Since release 3.16, there is a single configuration class `otb::DEMHandler` to manage elevation (in image projections or localization functions for example). This configuration is managed by the a proper instanciation and parameters setting of this class. These instanciations must be done before any call to geometric filters or functionalities. Ossim internal accesses to elevation are also configured by this class and this will ensure consistency throughout the library.

This class is a singleton, the New() method is deprecated and will be removed in future release. We need to use the `Instance()` method instead.

```
otb::DEMHandler::Pointer demHandler = otb::DEMHandler::Instance();
```

It allows to configure a directory containing DEM tiles (DTED or SRTM supported) using the `OpenDEMDirectory()` method. The `OpenGeoidFile()` method allows to input a geoid file as well. Last, a default height above ellipsoid can be set using the `SetDefaultHeightAboveEllipsoid()` method.

```
demHandler->SetDefaultHeightAboveEllipsoid(defaultHeight);

if(!demHandler->IsValidDEMDirectory(demdir.c_str()))
  {
  std::cerr<<"IsValidDEMDirectory("<<demdir<<") = false"<<std::endl;
  fail = true;
  }

demHandler->OpenDEMDirectory(demdir);
demHandler->OpenGeoidFile(geoid);
```

We can now retrieve height above ellipsoid or height above Mean Sea Level (MSL) using the methods `GetHeightAboveEllipsoid()` and `GetHeightAboveMSL()`. Outputs of these methods depend on the configuration of the class `otb::DEMHandler` and the different cases are:

For `GetHeightAboveEllipsoid()`:

- DEM and geoid both available: $dem\_value + geoid\_offset$
- No DEM but geoid available: geoid_offset
- DEM available, but no geoid: dem_value
- No DEM and no geoid available: default height above ellipsoid

For `GetHeightAboveMSL()`:

- DEM and geoid both available: srtm_value
- No DEM but geoid available: 0
- DEM available, but no geoid: srtm_value
- No DEM and no geoid available: 0

```
otb::DEMHandler::PointType point;
point[0] = longitude;
point[1] = latitude;

double height = -32768;
```

```
height = demHandler->GetHeightAboveMSL(point);
std::cout<<"height above MSL ("<<longitude<<","
         <<latitude<<") = "<<height<<" meters"<<std::endl;

height = demHandler->GetHeightAboveEllipsoid(point);
std::cout<<"height above ellipsoid ("<<longitude
         <<", "<<latitude<<") = "<<height<<" meters"<<std::endl;
```

Note that OSSIM internal calls for sensor modelling use the height above ellipsoid, and follow the same logic as the `GetHeightAboveEllipsoid()` method.

More examples about representing DEM are presented in section 23.1.4.

7.3 Reading and Writing Shapefiles and KML

The source code for this example can be found in the file `Examples/IO/VectorDataIOExample.cxx`.

Unfortunately, many vector data formats do not share the models for the data they represent. However, in some cases, when simple data is stored, it can be decomposed in simple objects as for instance polylines, polygons and points. This is the case for the Shapefile and the KML (Keyhole Markup Language) formats, for instance.

Even though specific reader/writer for Shapefile and the Google KML are available in OTB, we designed a generic approach for the IO of this kind of data.

The reader/writer for VectorData in OTB is able to access a variety of vector file formats (all OGR supported formats)

In section 11.4, you will find more information on how projections work for the vector data and how you can export the results obtained with OTB to the real world.

This example illustrates the use of OTB's vector data IO framework.

We will start by including the header files for the classes describing the vector data and the corresponding reader and writer.

```
#include "otbVectorData.h"
#include "otbVectorDataFileReader.h"
#include "otbVectorDataFileWriter.h"
```

We will also need to include the header files for the classes which model the individual objects that we get from the vector data structure.

```
#include "itkPreOrderTreeIterator.h"
#include "otbObjectList.h"
#include "otbPolygon.h"
```

We define the types for the vector data structure and the corresponding file reader.

```
typedef otb::VectorData<PixelType, 2> VectorDataType;

typedef otb::VectorDataFileReader<VectorDataType>
VectorDataFileReaderType;
```

We can now instantiate the reader and read the data.

```
VectorDataFileReaderType::Pointer reader = VectorDataFileReaderType::New();
reader->SetFileName(argv[1]);
reader->Update();
```

The vector data obtained from the reader will provide a tree of nodes containing the actual objects of the scene. This tree will be accessed using an `itk::PreOrderTreeIterator`.

```
typedef VectorDataType::DataTreeType            DataTreeType;
typedef itk::PreOrderTreeIterator<DataTreeType> TreeIteratorType;
```

In this example we will only read polygon objects from the input file before writing them to the output file. We define the type for the polygon object as well as an iterator to the vertices. The polygons obtained will be stored in an `otb::ObjectList`.

```
typedef otb::Polygon<double>                     PolygonType;
typedef PolygonType::VertexListConstIteratorType PolygonIteratorType;
typedef otb::ObjectList<PolygonType>             PolygonListType;

typedef PolygonListType::Iterator PolygonListIteratorType;

PolygonListType::Pointer polygonList = PolygonListType::New();
```

We get the data tree and instantiate an iterator to walk through it.

```
TreeIteratorType it(reader->GetOutput()->GetDataTree());

it.GoToBegin();
```

We check that the current object is a polygon using the `IsPolygonFeature()` method and get its exterior ring in order to store it into the list.

```
while (!it.IsAtEnd())
  {
  if (it.Get()->IsPolygonFeature())
    {
    polygonList->PushBack(it.Get()->GetPolygonExteriorRing());
    }
  ++it;
  }
```

Before writing the polygons to the output file, we have to build the vector data structure. This structure will be built up of nodes. We define the types needed for that.

```
VectorDataType::Pointer outVectorData = VectorDataType::New();

typedef VectorDataType::DataNodeType DataNodeType;
```

We fill the data structure with the nodes. The root node is a document which is composed of folders. A list of polygons can be seen as a multi polygon object.

```
DataNodeType::Pointer document = DataNodeType::New();
document->SetNodeType(otb::DOCUMENT);
document->SetNodeId("polygon");
DataNodeType::Pointer folder = DataNodeType::New();
folder->SetNodeType(otb::FOLDER);
DataNodeType::Pointer multiPolygon = DataNodeType::New();
multiPolygon->SetNodeType(otb::FEATURE_MULTIPOLYGON);
```

We assign these objects to the data tree stored by the vector data object.

```
DataTreeType::Pointer tree = outVectorData->GetDataTree();
DataNodeType::Pointer root = tree->GetRoot()->Get();

tree->Add(document, root);
tree->Add(folder, document);
tree->Add(multiPolygon, folder);
```

We can now iterate through the polygon list and fill the vector data structure.

```
for (PolygonListType::Iterator it = polygonList->Begin();
     it != polygonList->End(); ++it)
  {
  DataNodeType::Pointer newPolygon = DataNodeType::New();
  newPolygon->SetPolygonExteriorRing(it.Get());
  tree->Add(newPolygon, multiPolygon);
  }
```

And finally we write the vector data to a file using a generic `otb::VectorDataFileWriter`.

```
typedef otb::VectorDataFileWriter<VectorDataType> WriterType;

WriterType::Pointer writer = WriterType::New();
writer->SetInput(outVectorData);
writer->SetFileName(argv[2]);
writer->Update();
```

This example can convert an ESRI Shapefile to a MapInfo File but you can also access with the same OTB source code to a PostgreSQL datasource, using a connection string as : PG:”dbname=’databasename’ host=’addr’ port=’5432’ user=’x’ password=’y’” Starting with GDAL 1.6.0, the set of tables to be scanned can be overridden by specifying tables=schema.table.

7.4 Handling large vector data through OGR

The source code for this example can be found in the file `Examples/IO/OGRWrappersExample.cxx`.

Starting with the version 3.14.0 of the OTB library, a wrapper around OGR API is provided. The purposes of the wrapper are:

- to permit OTB to handle very large vector data sets;
- and to offer a modern (in the RAII sense) interface to handle vector data.

As OGR already provides a rich set of geometric related data, as well as the algorithms to manipulate and serialize them, we've decided to wrap it into a new *exception-safe* interface.

This example illustrates the use of OTB's OGR wrapper framework. This program takes a source of polygons (a shape file for instance) as input and produces a datasource of multi-polygons as output.

We will start by including the header files for the OGR wrapper classes, plus other header files that are out of scope here.

```
#include "otbOGRDataSourceWrapper.h"
```

The following declarations will permit to merge the `otb::ogr::Fields` from each `otb::ogr::Feature` into list-fields. We'll get back to this point later.

```
#include <string>
#include <vector>
#include <boost/variant.hpp>
#include "otbJoinContainer.h"

typedef std::vector<int>                                    IntList_t;
typedef std::vector<std::string>                            StringList_t;
typedef std::vector<double>                                 RealList_t;
// TODO: handle non recognized fields
typedef boost::variant<IntList_t, StringList_t, RealList_t> AnyListField_t;
typedef std::vector<AnyListField_t>                         AnyListFieldList_t;

AnyListFieldList_t prepareNewFields(
  OGRFeatureDefn /*const*/& defn, otb::ogr::Layer & destLayer);
void printField(
  otb::ogr::Field const& field, AnyListField_t const& newListField);
void assignField(
  otb::ogr::Field field, AnyListField_t const& newListFieldValue);
void  pushFieldsToFieldLists(
  otb::ogr::Feature const& inputFeature, AnyListFieldList_t & field);
```

We caw now instantiate first the input `otb::ogr::DataSource`.

```
    otb::ogr::DataSource::Pointer source = otb::ogr::DataSource::New(
      argv[1], otb::ogr::DataSource::Modes::Read);
```

And then, we can instantiate the output `otb::ogr::DataSource` and its unique `otb::ogr::Layer` multi-polygons.

```
    otb::ogr::DataSource::Pointer destination = otb::ogr::DataSource::New(
      argv[2], otb::ogr::DataSource::Modes::Update_LayerCreateOnly);
    otb::ogr::Layer destLayer = destination->CreateLayer(
      argv[2], 0, wkbMultiPolygon);
```

The data obtained from the reader mimics the interface of `OGRDataSource`. To access the geometric objects stored, we need first to iterate on the `otb::ogr::Layers` from the `otb::ogr::DataSource`, then on the `otb::ogr::Feature` from each layer.

```
    // for (auto const& inputLayer : *source)
    for (otb::ogr::DataSource::const_iterator lb=source->begin(), le=source->end()
; lb != le
; ++lb)
      {
      otb::ogr::Layer const& inputLayer = *lb;
```

In this example we will only read polygon objects from the input file before writing them to the output file. As all features from a layer share the same geometric type, we can filter on the layer geometric type.

```
      if (inputLayer.GetGeomType() != wkbPolygon)
        {
        std::cout << "Warning: Ignoring layer: ";
        inputLayer.PrintSelf(std::cout, 2);
        continue; // skip to next layer
        }
```

In order to prepare the fields for the new layer, we first need to extract the fields definition from the input layer in order to deduce the new fields of the result layer.

```
      OGRFeatureDefn & sourceFeatureDefn = inputLayer.GetLayerDefn();
      AnyListFieldList_t fields = prepareNewFields(sourceFeatureDefn, destLayer);
```

The result layer will contain only one feature, per input layer, that stores a multi-polygon shape. All geometric shapes are plain `OGRGeometry` objects.

```
      OGRMultiPolygon destGeometry; // todo: use UniqueGeometryPtr
```

The transformation algorithm is as simple as aggregating all the polygons from the features from the input layer into the destination multi-polygon geometric object.

Note that `otb::ogr::Feature::GetGeometry()` provides a direct access to a non-mutable `OGRGeometry` pointer and that `OGRGeometryCollection::addGeometry()` copies the received pointer. As a consequence, the following code is optimal regarding the geometric objects manipulated.

This is also at this point that we fetch the field values from the input features to accumulate them into the `fields` list.

```
      // for (auto const& inputFeature : inputLayer)
      for (otb::ogr::Layer::const_iterator fb=inputLayer.begin(), fe=inputLayer.end()
; fb != fe
; ++fb)
        {
        otb::ogr::Feature const& inputFeature = *fb;
        destGeometry.addGeometry(inputFeature.GetGeometry());
        pushFieldsToFieldLists(inputFeature,fields);
        } // for each feature
```

Then the new geometric object can be added to a new feature, that will be eventually added to the destination layer.

```
      otb::ogr::Feature newFeature(destLayer.GetLayerDefn());
      newFeature.SetGeometry(&destGeometry); // SetGeom -> copies
```

We set here the fields of the new feature with the ones accumulated over the features from the input layer.

```
      for (size_t i=0, N=sourceFeatureDefn.GetFieldCount(); i!=N; ++i)
        {
        printField(newFeature[i], fields[i]);
        assignField(newFeature[i], fields[i]);
        }
```

Finally we add (with `otb::ogr::Layer::CreateFeature()` the new feature to the destination layer, and we can process the next layer from the input datasource.

```
      destLayer.CreateFeature(newFeature); // adds feature to the layer
      } // for each layer
```

In order to *simplify* the manipulation of `otb::ogr::Fields` and to avoid copy-paste for each possible case of field-type, this example relies on boost.Variant.

As such, we have defined `AnyListField_t` as a variant type on all possible types of field. Then, the manipulation of the variant field values is done through the templatized functions `otb::ogr::Field::SetValue<>()` and `otb::ogr::Field::GetValue<>()`, from the various variant-visitors.

Before using the visitors, we need to operate a switch on the exact type of each field from the input layers. An empty field-values container is first added to the set of fields containers. Finally, the destination layer is completed with a new field of the right deduced type.

```
AnyListFieldList_t prepareNewFields(
  OGRFeatureDefn /*const*/& defn, otb::ogr::Layer & destLayer)
{
  AnyListFieldList_t fields;
  for (size_t i=0, N=defn.GetFieldCount(); i!=N; ++i)
    {
    const char* name = defn.GetFieldDefn(i)->GetNameRef();
```

```
    OGRFieldType type  = static_cast<OGRFieldType>(-1);
    switch (defn.GetFieldDefn(i)->GetType())
      {
    case OFTInteger:
      fields.push_back (IntList_t());
      type = OFTIntegerList;
      break;
    case OFTString:
      fields.push_back (StringList_t());
      type = OFTStringList;
      break;
    case OFTReal:
      fields.push_back (RealList_t());
      type = OFTRealList;
      break;
    default:
      std::cerr << "Unsupported field type: " <<
        OGRFieldDefn::GetFieldTypeName(defn.GetFieldDefn(i)->GetType())
        << " for " << name << "\n";
      break;
      }
    OGRFieldDefn newFieldDefn(name, type); // name is duplicated here => no dangling pointer
    destLayer.CreateField(newFieldDefn, false);
    }
  return fields;
}
```

The first visitor, `PushVisitor()`, takes the value from one field and pushes it into a container of list-variant. The type of the field to fetch is deduced from the type of the values stored in the container. It is called by `pushFieldsToFieldLists()`, that for each field of the input feature applies the visitor on the container.

```
struct PushVisitor : boost::static_visitor<>
{
  PushVisitor(otb::ogr::Field const& f) : m_f(f) {}

  template <typename T> void operator()(T & container) const
    {
    typedef typename T::value_type value_type;
    value_type const value = m_f.GetValue<value_type>();
    container.push_back(value);
    }
private:
  otb::ogr::Field const& m_f;
};

void  pushFieldsToFieldLists(
  otb::ogr::Feature const& inputFeature, AnyListFieldList_t & fields)
{
  // For each field
  for (size_t i=0, N=inputFeature.GetSize(); i!=N; ++i)
    {
    otb::ogr::Field field = inputFeature[i];
    boost::apply_visitor(PushVisitor(field), fields[i]);
```

```
    }
}
```

A second simple visitor, `PrintVisitor`, is defined to trace the values of each field (which contains a list of typed data (integers, strings or reals).

```
struct PrintVisitor : boost::static_visitor<>
{
  template <typename T> void operator()(T const& container) const
    {
    otb::Join(std::cout, container, ", ");
    }
};

void printField(otb::ogr::Field const& field, AnyListField_t const& newListField)
{
  std::cout << field.GetName() << " -> ";
  boost::apply_visitor(PrintVisitor(), newListField);
}
```

The third visitor, `SetFieldVisitor`, sets the field of the destination features, which have been accumulated in the list of typed values.

```
struct SetFieldVisitor : boost::static_visitor<>
{
  SetFieldVisitor(otb::ogr::Field f) : m_f(f) {}
  // operator() from visitors are expected to be const
  template <typename T> void operator()(T const& container) const
    {
    m_f.SetValue(container);
    }
private:
  otb::ogr::Field mutable m_f; // this is a proxy -> a reference in a sort
};

void assignField(otb::ogr::Field field, AnyListField_t const& newListFieldValue)
{
  boost::apply_visitor(SetFieldVisitor(field), newListFieldValue);
}
```

Note that this example does not handle the case when the input layers don't share a same fields-definition.

CHAPTER

EIGHT

BASIC FILTERING

This chapter introduces the most commonly used filters found in OTB. Most of these filters are intended to process images. They will accept one or more images as input and will produce one or more images as output. OTB is based ITK's data pipeline architecture in which the output of one filter is passed as input to another filter. (See Section 3.5 on page 34 for more information.)

8.1 Thresholding

The thresholding operation is used to change or identify pixel values based on specifying one or more values (called the *threshold* value). The following sections describe how to perform thresholding operations using OTB.

8.1.1 Binary Thresholding

The source code for this example can be found in the file
`Examples/Filtering/BinaryThresholdImageFilter.cxx`.

This example illustrates the use of the binary threshold image filter. This filter is used to transform an image into a binary image by changing the pixel values according to the rule illustrated in Figure 8.1. The user defines two thresholds—Upper and Lower—and two intensity values—Inside and Outside. For each pixel in the input image, the value of the pixel is compared with the lower and upper thresholds. If the pixel value is inside the range defined by $[Lower, Upper]$ the output pixel is assigned the InsideValue. Otherwise the output pixels are assigned to the OutsideValue. Thresholding is commonly applied as the last operation of a segmentation pipeline.

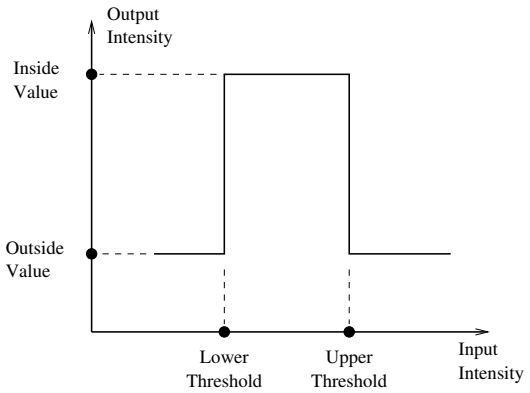


Figure 8.1: Transfer function of the BinaryThresholdImageFilter.

The first step required to use the `itk::BinaryThresholdImageFilter` is to include its header file.

```
#include "itkBinaryThresholdImageFilter.h"
```

The next step is to decide which pixel types to use for the input and output images.

```
typedef  unsigned char InputPixelType;
typedef  unsigned char OutputPixelType;
```

The input and output image types are now defined using their respective pixel types and dimensions.

```
typedef otb::Image<InputPixelType,  2> InputImageType;
typedef otb::Image<OutputPixelType, 2> OutputImageType;
```

The filter type can be instantiated using the input and output image types defined above.

```
typedef itk::BinaryThresholdImageFilter<
    InputImageType, OutputImageType>  FilterType;
```

An `otb::ImageFileReader` class is also instantiated in order to read image data from a file. (See Section 6 on page 97 for more information about reading and writing data.)

```
typedef otb::ImageFileReader<InputImageType> ReaderType;
```

An `otb::ImageFileWriter` is instantiated in order to write the output image to a file.

```
typedef otb::ImageFileWriter<InputImageType> WriterType;
```

Both the filter and the reader are created by invoking their `New()` methods and assigning the result to `itk::SmartPointer`s.

```
ReaderType::Pointer reader = ReaderType::New();
FilterType::Pointer filter = FilterType::New();
```

The image obtained with the reader is passed as input to the BinaryThresholdImageFilter.

```
filter->SetInput(reader->GetOutput());
```

The method `SetOutsideValue()` defines the intensity value to be assigned to those pixels whose intensities are outside the range defined by the lower and upper thresholds. The method `SetInsideValue()` defines the intensity value to be assigned to pixels with intensities falling inside the threshold range.

```
filter->SetOutsideValue(outsideValue);
filter->SetInsideValue(insideValue);
```

The methods `SetLowerThreshold()` and `SetUpperThreshold()` define the range of the input image intensities that will be transformed into the `InsideValue`. Note that the lower and upper thresholds are values of the type of the input image pixels, while the inside and outside values are of the type of the output image pixels.

```
filter->SetLowerThreshold(lowerThreshold);
filter->SetUpperThreshold(upperThreshold);
```

The execution of the filter is triggered by invoking the `Update()` method. If the filter's output has been passed as input to subsequent filters, the `Update()` call on any posterior filters in the pipeline will indirectly trigger the update of this filter.

```
filter->Update();
```

Figure 8.2 illustrates the effect of this filter on a ROI of a Spot 5 image of an agricultural area. This figure shows the limitations of this filter for performing segmentation by itself. These limitations are particularly noticeable in noisy images and in images lacking spatial uniformity.

The following classes provide similar functionality:

- `itk::ThresholdImageFilter`

8.1.2 General Thresholding

The source code for this example can be found in the file `Examples/Filtering/ThresholdImageFilter.cxx`.

This example illustrates the use of the `itk::ThresholdImageFilter`. This filter can be used to transform the intensity levels of an image in three different ways.

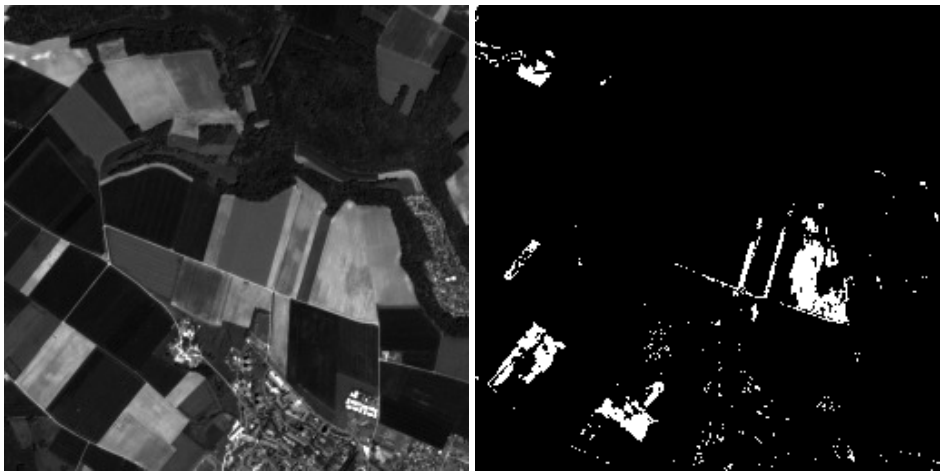


Figure 8.2: Effect of the BinaryThresholdImageFilter on a ROI of a Spot 5 image.

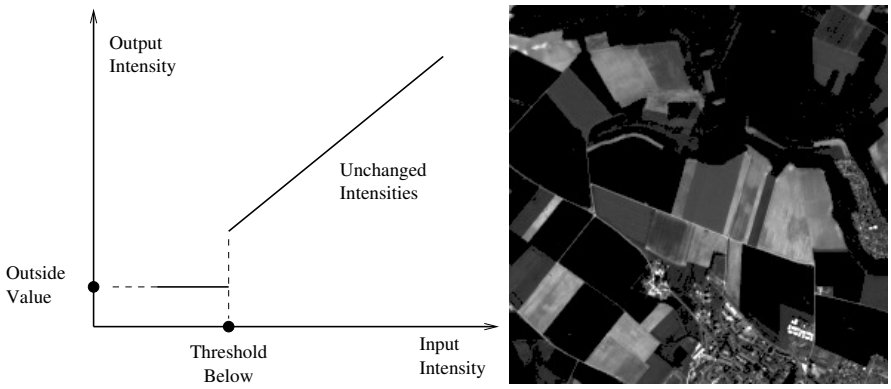


Figure 8.3: ThresholdImageFilter using the threshold-below mode.

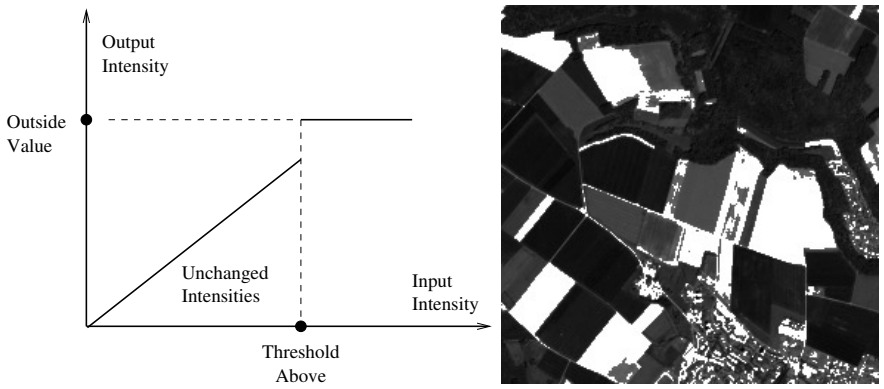


Figure 8.4: ThresholdImageFilter using the threshold-above mode.

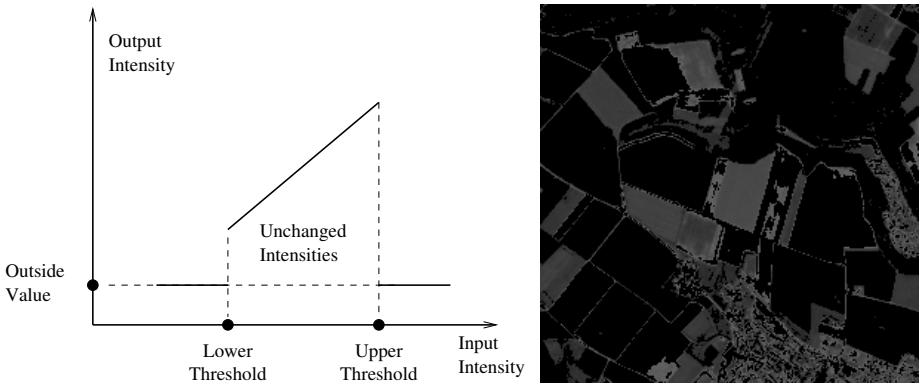


Figure 8.5: ThresholdImageFilter using the threshold-outside mode.

- First, the user can define a single threshold. Any pixels with values below this threshold will be replaced by a user defined value, called here the `OutsideValue`. Pixels with values above the threshold remain unchanged. This type of thresholding is illustrated in Figure 8.3.
- Second, the user can define a particular threshold such that all the pixels with values above the threshold will be replaced by the `OutsideValue`. Pixels with values below the threshold remain unchanged. This is illustrated in Figure 8.4.
- Third, the user can provide two thresholds. All the pixels with intensity values inside the range defined by the two thresholds will remain unchanged. Pixels with values outside this range will be assigned to the `OutsideValue`. This is illustrated in Figure 8.5.

The following methods choose among the three operating modes of the filter.

- `ThresholdBelow()`
- `ThresholdAbove()`
- `ThresholdOutside()`

The first step required to use this filter is to include its header file.

```
#include "itkThresholdImageFilter.h"
```

Then we must decide what pixel type to use for the image. This filter is templated over a single image type because the algorithm only modifies pixel values outside the specified range, passing the rest through unchanged.

```
  typedef  unsigned char PixelType;
```

The image is defined using the pixel type and the dimension.

```
  typedef otb::Image<PixelType,  2> ImageType;
```

The filter can be instantiated using the image type defined above.

```
  typedef itk::ThresholdImageFilter<ImageType> FilterType;
```

An `otb::ImageFileReader` class is also instantiated in order to read image data from a file.

```
  typedef otb::ImageFileReader<ImageType> ReaderType;
```

An `otb::ImageFileWriter` is instantiated in order to write the output image to a file.

```
  typedef otb::ImageFileWriter<ImageType> WriterType;
```

Both the filter and the reader are created by invoking their `New()` methods and assigning the result to SmartPointers.

```
ReaderType::Pointer reader = ReaderType::New();
FilterType::Pointer filter = FilterType::New();
```

The image obtained with the reader is passed as input to the `itk::ThresholdImageFilter`.

```
filter->SetInput(reader->GetOutput());
```

The method `SetOutsideValue()` defines the intensity value to be assigned to those pixels whose intensities are outside the range defined by the lower and upper thresholds.

```
filter->SetOutsideValue(0);
```

The method `ThresholdBelow()` defines the intensity value below which pixels of the input image will be changed to the `OutsideValue`.

```
filter->ThresholdBelow(40);
```

The filter is executed by invoking the `Update()` method. If the filter is part of a larger image processing pipeline, calling `Update()` on a downstream filter will also trigger update of this filter.

```
filter->Update();
```

The output of this example is shown in Figure 8.3. The second operating mode of the filter is now enabled by calling the method `ThresholdAbove()`.

```
filter->ThresholdAbove(100);
filter->SetOutsideValue(255);
filter->Update();
```

Updating the filter with this new setting produces the output shown in Figure 8.4. The third operating mode of the filter is enabled by calling `ThresholdOutside()`.

```
filter->ThresholdOutside(40, 100);
filter->SetOutsideValue(0);
filter->Update();
```

The output of this third, "band-pass" thresholding mode is shown in Figure 8.5.

The examples in this section also illustrate the limitations of the thresholding filter for performing segmentation by itself. These limitations are particularly noticeable in noisy images and in images lacking spatial uniformity.

The following classes provide similar functionality:

- `itk::BinaryThresholdImageFilter`

8.1.3 Threshold to Point Set

The source code for this example can be found in the file
`Examples/FeatureExtraction/ThresholdToPointSetExample.cxx`.

Sometimes, it may be more valuable not to get an image from the threshold step but rather a list of coordinates. This can be done with the `otb::ThresholdImageToPointSetFilter`.

The following example illustrates the use of the `otb::ThresholdImageToPointSetFilter` which provide a list of points within given thresholds. Points set are described in section 5.2 on page 78.

The first step required to use this filter is to include the header

```
#include "otbThresholdImageToPointSetFilter.h"
#include "itkPointSet.h"
```

The next step is to decide which pixel types to use for the input image and the Point Set as well as their dimension.

```
typedef unsigned char PixelType;
const unsigned int Dimension = 2;

typedef otb::Image<PixelType, Dimension>    ImageType;
typedef itk::PointSet<PixelType, Dimension> PointSetType;
```

A reader is instanciated to read the input image

```
typedef otb::ImageFileReader<ImageType> ReaderType;
ReaderType::Pointer reader = ReaderType::New();

const char * filenamereader = argv[1];
reader->SetFileName(filenamereader);
```

We get the parameters from the command line for the threshold filter. The lower and upper thresholds parameters are similar to those of the `itk::BinaryThresholdImageFilter` (see Section 8.1.1 on page 133 for more information).

```
int lowerThreshold = atoi(argv[2]);
int upperThreshold = atoi(argv[3]);
```

Then we create the ThresholdImageToPointSetFilter and we pass the parameters.

```
typedef otb::ThresholdImageToPointSetFilter
<ImageType, PointSetType> FilterThresholdType;
FilterThresholdType::Pointer filterThreshold = FilterThresholdType::New();
filterThreshold->SetLowerThreshold(lowerThreshold);
filterThreshold->SetUpperThreshold(upperThreshold);
filterThreshold->SetInput(0, reader->GetOutput());
```

To manipulate and display the result of this filter, we manually instanciate a point set and we call the `Update()` method on the threshold filter to trigger the pipeline execution.

After this step, the `pointSet` variable contains the point set.

```
PointSetType::Pointer pointSet     = PointSetType::New();
pointSet = filterThreshold->GetOutput();

filterThreshold->Update();
```

To display each point, we create an iterator on the list of points, which is accessible through the method `GetPoints()` of the PointSet.

```
typedef PointSetType::PointsContainer ContainerType;
ContainerType* pointsContainer = pointSet->GetPoints();
typedef ContainerType::Iterator IteratorType;
IteratorType itList = pointsContainer->Begin();
```

A while loop enable us to through the list a display the coordinate of each point.

```
while (itList != pointsContainer->End())
  {
  std::cout << itList.Value() << std::endl;
  ++itList;
  }
```

8.2 Mathematical operations on images

OTB and ITK provide a lot of filters allowing to perform basic operations on image layers (thresholding, ratio, layers combinations...). It allows to create a processing chain defining at each step operations and to combine them in the data pipeline. But the library offers also the possibility to perform more generic complex mathematical operation on images in a single filter: the `otb::BandMathImageFilter`.

The source code for this example can be found in the file `Examples/BasicFilters/BandMathFilterExample.cxx`.

This filter is based on the mathematical parser library muParser. The built in functions and operators list is available at: `http://muparser.sourceforge.net/mup_features.html`.

In order to use this filter, at least one input image is to be set. An associated variable name can be specified or not by using the corresponding SetNthInput method. For the nth input image, if no associated variable name has been specified, a default variable name is given by concatenating the letter ”b” (for band) and the corresponding input index.

The next step is to set the expression according to the variable names. For example, in the default case with three input images the following expression is valid : ”(b1+b2)*b3”.

We start by including the needed header file. The aim of this example is to compute the Normalized Difference Vegetation Index (NDVI) from a multispecral image and perform a threshold on this indice to extract area containing a dense vegetation canopy.

```
#include "otbBandMathImageFilter.h"
```

We start by the classical typedefs needed for reading and writing the images. The otb::BandMathImageFilter class works with otb::Image as input so we need to define additional filters to extract each layer of the multispectral image

```
  typedef double
PixelType;
  typedef otb::VectorImage<PixelType, 2>
InputImageType;
  typedef otb::Image<PixelType, 2>
OutputImageType;
  typedef otb::ImageList<OutputImageType>
ImageListType;
  typedef OutputImageType::PixelType
VPixelType;
  typedef otb::VectorImageToImageListFilter<InputImageType, ImageListType>
  VectorImageToImageListType;
  typedef otb::ImageFileReader<InputImageType>
ReaderType;
  typedef otb::ImageFileWriter<OutputImageType>
WriterType;
```

We can now define the type for the filter:

```
  typedef otb::BandMathImageFilter<OutputImageType>   FilterType;
```

We instantiate the filter, the reader, and the writer:

```
  ReaderType::Pointer reader = ReaderType::New();
  WriterType::Pointer writer = WriterType::New();

  FilterType::Pointer filter = FilterType::New();

  writer->SetInput(filter->GetOutput());
  reader->SetFileName(argv[1]);
  writer->SetFileName(argv[2]);
```

We need now to extract now each band from the input otb::VectorImage, it illustrates the use of the otb::VectorImageToImageList. Each extracted layer are inputs of the otb::BandMathImageFilter:

```
  VectorImageToImageListType::Pointer imageList = VectorImageToImageListType::New();
  imageList->SetInput(reader->GetOutput());

  imageList->UpdateOutputInformation();

  const unsigned int nbBands = reader->GetOutput()->GetNumberOfComponentsPerPixel();

  for(unsigned int j = 0; j < nbBands; ++j)
      {
```

Figure 8.6: From left to right: Original image, thresholded NDVI indice.

```
    filter->SetNthInput(j, imageList->GetOutput()->GetNthElement(j));
    }
```

Now we can define the mathematical expression to perform on the layers (b1, b2, b3, b4). The filter takes advantage of the parsing capabilities of the muParser library and allows to set the expression as on a digital calculator.

The expression below returns 255 if the ratio $(NIR-RED)/(NIR+RED)$ is greater than 0.4 and 0 if not.

```
filter->SetExpression("if((b4-b3)/(b4+b3) > 0.4, 255, 0)");
```

We can now plug the pipeline and run it.

```
writer->Update();
```

The muParser library offers also the possibility to extended existing built-in functions. For example, you can use the OTB expression "ndvi(b3, b4)" with the filter. The mathematical expression would be in this case *if(ndvi*$(b3,b4) > 0.4$*, 255, 0)*. It will return the same result.

Figure 8.6 shows the result of the threshold over the NDVI indice to a Quickbird image.

8.3 Gradients

Computation of gradients is a fairly common operation in image processing. The term "gradient" may refer in some contexts to the gradient vectors and in others to the magnitude of the gradient vec-

tors. ITK filters attempt to reduce this ambiguity by including the *magnitude* term when appropriate. ITK provides filters for computing both the image of gradient vectors and the image of magnitudes.

8.3.1 Gradient Magnitude

The source code for this example can be found in the file
`Examples/Filtering/GradientMagnitudeImageFilter.cxx`.

The magnitude of the image gradient is extensively used in image analysis, mainly to help in the determination of object contours and the separation of homogeneous regions. The `itk::GradientMagnitudeImageFilter` computes the magnitude of the image gradient at each pixel location using a simple finite differences approach. For example, in the case of $2D$ the computation is equivalent to convolving the image with masks of type

-1	0	1

-1
0
1

then adding the sum of their squares and computing the square root of the sum.

This filter will work on images of any dimension thanks to the internal use of `itk::NeighborhoodIterator` and `itk::NeighborhoodOperator`.

The first step required to use this filter is to include its header file.

```
#include "itkGradientMagnitudeImageFilter.h"
```

Types should be chosen for the pixels of the input and output images.

```
typedef    float InputPixelType;
typedef    float OutputPixelType;
```

The input and output image types can be defined using the pixel types.

```
typedef otb::Image<InputPixelType,  2> InputImageType;
typedef otb::Image<OutputPixelType, 2> OutputImageType;
```

The type of the gradient magnitude filter is defined by the input image and the output image types.

```
typedef itk::GradientMagnitudeImageFilter<
    InputImageType, OutputImageType>  FilterType;
```

A filter object is created by invoking the `New()` method and assigning the result to a `itk::SmartPointer`.

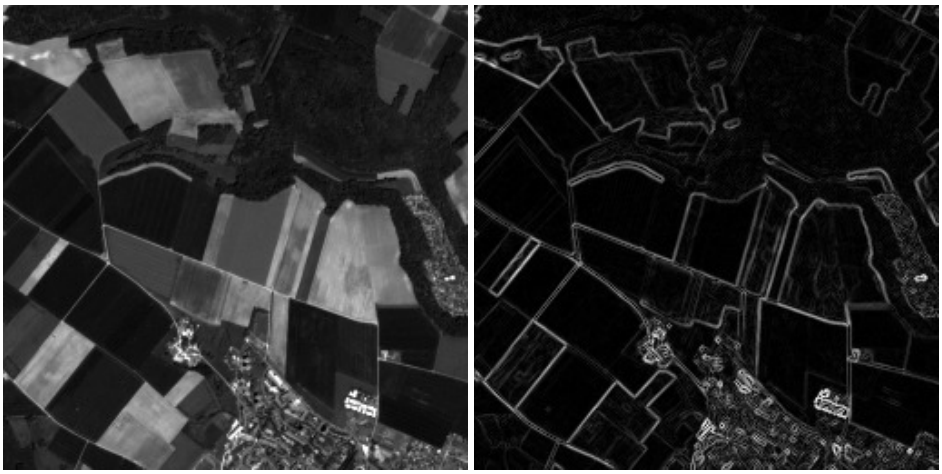


Figure 8.7: Effect of the GradientMagnitudeImageFilter.

```
FilterType::Pointer filter = FilterType::New();
```

The input image can be obtained from the output of another filter. Here, the source is an image reader.

```
filter->SetInput(reader->GetOutput());
```

Finally, the filter is executed by invoking the `Update()` method.

```
filter->Update();
```

If the output of this filter has been connected to other filters in a pipeline, updating any of the downstream filters will also trigger an update of this filter. For example, the gradient magnitude filter may be connected to an image writer.

```
rescaler->SetInput(filter->GetOutput());
writer->SetInput(rescaler->GetOutput());
writer->Update();
```

Figure 8.7 illustrates the effect of the gradient magnitude. The figure shows the sensitivity of this filter to noisy data.

Attention should be paid to the image type chosen to represent the output image since the dynamic range of the gradient magnitude image is usually smaller than the dynamic range of the input image. As always, there are exceptions to this rule, for example, images of man-made objects that contain high contrast objects.

This filter does not apply any smoothing to the image before computing the gradients. The results can therefore be very sensitive to noise and may not be best choice for scale space analysis.

8.3.2 Gradient Magnitude With Smoothing

The source code for this example can be found in the file
`Examples/Filtering/GradientMagnitudeRecursiveGaussianImageFilter.cxx`.

Differentiation is an ill-defined operation over digital data. In practice it is convenient to define a scale in which the differentiation should be performed. This is usually done by preprocessing the data with a smoothing filter. It has been shown that a Gaussian kernel is the most convenient choice for performing such smoothing. By choosing a particular value for the standard deviation (σ) of the Gaussian, an associated scale is selected that ignores high frequency content, commonly considered image noise.

The `itk::GradientMagnitudeRecursiveGaussianImageFilter` computes the magnitude of the image gradient at each pixel location. The computational process is equivalent to first smoothing the image by convolving it with a Gaussian kernel and then applying a differential operator. The user selects the value of σ.

Internally this is done by applying an IIR [1] filter that approximates a convolution with the derivative of the Gaussian kernel. Traditional convolution will produce a more accurate result, but the IIR approach is much faster, especially using large σs [36, 37].

GradientMagnitudeRecursiveGaussianImageFilter will work on images of any dimension by taking advantage of the natural separability of the Gaussian kernel and its derivatives.

The first step required to use this filter is to include its header file.

```
#include "itkGradientMagnitudeRecursiveGaussianImageFilter.h"
```

Types should be instantiated based on the pixels of the input and output images.

```
  typedef    float InputPixelType;
  typedef    float OutputPixelType;
```

With them, the input and output image types can be instantiated.

```
  typedef otb::Image<InputPixelType,  2> InputImageType;
  typedef otb::Image<OutputPixelType, 2> OutputImageType;
```

The filter type is now instantiated using both the input image and the output image types.

```
  typedef itk::GradientMagnitudeRecursiveGaussianImageFilter<
      InputImageType, OutputImageType>  FilterType;
```

[1] Infinite Impulse Response

Figure 8.8: Effect of the GradientMagnitudeRecursiveGaussianImageFilter.

A filter object is created by invoking the `New()` method and assigning the result to a `itk::SmartPointer`.

```
FilterType::Pointer filter = FilterType::New();
```

The input image can be obtained from the output of another filter. Here, an image reader is used as source.

```
filter->SetInput(reader->GetOutput());
```

The standard deviation of the Gaussian smoothing kernel is now set.

```
filter->SetSigma(sigma);
```

Finally the filter is executed by invoking the `Update()` method.

```
filter->Update();
```

If connected to other filters in a pipeline, this filter will automatically update when any downstream filters are updated. For example, we may connect this gradient magnitude filter to an image file writer and then update the writer.

```
rescaler->SetInput(filter->GetOutput());
writer->SetInput(rescaler->GetOutput());
writer->Update();
```

Figure 8.8 illustrates the effect of this filter using σ values of 3 (left) and 5 (right). The figure shows how the sensitivity to noise can be regulated by selecting an appropriate σ. This type of scale-tunable filter is suitable for performing scale-space analysis.

Attention should be paid to the image type chosen to represent the output image since the dynamic range of the gradient magnitude image is usually smaller than the dynamic range of the input image.

8.3.3 Derivative Without Smoothing

The source code for this example can be found in the file
`Examples/Filtering/DerivativeImageFilter.cxx`.

The `itk::DerivativeImageFilter` is used for computing the partial derivative of an image, the derivative of an image along a particular axial direction.

The header file corresponding to this filter should be included first.

```
#include "itkDerivativeImageFilter.h"
```

Next, the pixel types for the input and output images must be defined and, with them, the image types can be instantiated. Note that it is important to select a signed type for the image, since the values of the derivatives will be positive as well as negative.

```
typedef   float InputPixelType;
typedef   float OutputPixelType;

const unsigned int Dimension = 2;

typedef otb::Image<InputPixelType,  Dimension> InputImageType;
typedef otb::Image<OutputPixelType, Dimension> OutputImageType;
```

Using the image types, it is now possible to define the filter type and create the filter object.

```
typedef itk::DerivativeImageFilter<
    InputImageType, OutputImageType>  FilterType;

FilterType::Pointer filter = FilterType::New();
```

The order of the derivative is selected with the `SetOrder()` method. The direction along which the derivative will be computed is selected with the `SetDirection()` method.

```
filter->SetOrder(atoi(argv[4]));
filter->SetDirection(atoi(argv[5]));
```

The input to the filter can be taken from any other filter, for example a reader. The output can be passed down the pipeline to other filters, for example, a writer. An update call on any downstream filter will trigger the execution of the derivative filter.

```
filter->SetInput(reader->GetOutput());
writer->SetInput(filter->GetOutput());
writer->Update();
```

Figure 8.9 illustrates the effect of the DerivativeImageFilter. The derivative is taken along the x direction. The sensitivity to noise in the image is evident from this result.

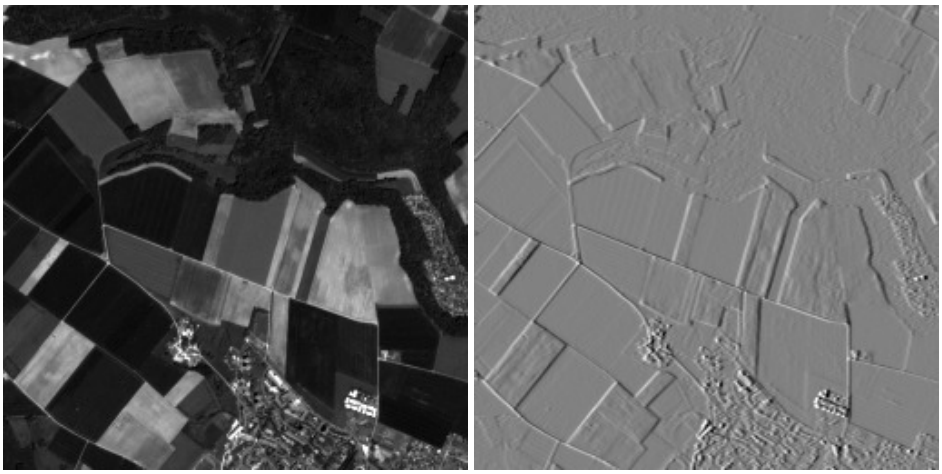


Figure 8.9: Effect of the Derivative filter.

8.4 Second Order Derivatives

8.4.1 Laplacian Filters

Laplacian Filter Recursive Gaussian

The source code for this example can be found in the file
`Examples/Filtering/LaplacianRecursiveGaussianImageFilter1.cxx`.

This example illustrates how to use the `itk::RecursiveGaussianImageFilter` for computing the Laplacian of an image.

The first step required to use this filter is to include its header file.

```
#include "itkRecursiveGaussianImageFilter.h"
```

Types should be selected on the desired input and output pixel types.

```
  typedef    float InputPixelType;
  typedef    float OutputPixelType;
```

The input and output image types are instantiated using the pixel types.

```
  typedef otb::Image<InputPixelType,  2> InputImageType;
  typedef otb::Image<OutputPixelType, 2> OutputImageType;
```

The filter type is now instantiated using both the input image and the output image types.

```
typedef itk::RecursiveGaussianImageFilter<
    InputImageType, OutputImageType>  FilterType;
```

This filter applies the approximation of the convolution along a single dimension. It is therefore necessary to concatenate several of these filters to produce smoothing in all directions. In this example, we create a pair of filters since we are processing a $2D$ image. The filters are created by invoking the `New()` method and assigning the result to a `itk::SmartPointer`.

We need two filters for computing the X component of the Laplacian and two other filters for computing the Y component.

```
FilterType::Pointer filterX1 = FilterType::New();
FilterType::Pointer filterY1 = FilterType::New();

FilterType::Pointer filterX2 = FilterType::New();
FilterType::Pointer filterY2 = FilterType::New();
```

Since each one of the newly created filters has the potential to perform filtering along any dimension, we have to restrict each one to a particular direction. This is done with the `SetDirection()` method.

```
filterX1->SetDirection(0);     // 0 --> X direction
filterY1->SetDirection(1);     // 1 --> Y direction

filterX2->SetDirection(0);     // 0 --> X direction
filterY2->SetDirection(1);     // 1 --> Y direction
```

The `itk::RecursiveGaussianImageFilter` can approximate the convolution with the Gaussian or with its first and second derivatives. We select one of these options by using the `SetOrder()` method. Note that the argument is an `enum` whose values can be `ZeroOrder`, `FirstOrder` and `SecondOrder`. For example, to compute the x partial derivative we should select `FirstOrder` for x and `ZeroOrder` for y. Here we want only to smooth in x and y, so we select `ZeroOrder` in both directions.

```
filterX1->SetOrder(FilterType::ZeroOrder);
filterY1->SetOrder(FilterType::SecondOrder);

filterX2->SetOrder(FilterType::SecondOrder);
filterY2->SetOrder(FilterType::ZeroOrder);
```

There are two typical ways of normalizing Gaussians depending on their application. For scale-space analysis it is desirable to use a normalization that will preserve the maximum value of the input. This normalization is represented by the following equation.

$$\frac{1}{\sigma\sqrt{2\pi}} \tag{8.1}$$

In applications that use the Gaussian as a solution of the diffusion equation it is desirable to use a

normalization that preserve the integral of the signal. This last approach can be seen as a conservation of mass principle. This is represented by the following equation.

$$\frac{1}{\sigma^2\sqrt{2\pi}} \tag{8.2}$$

The `itk::RecursiveGaussianImageFilter` has a boolean flag that allows users to select between these two normalization options. Selection is done with the method `SetNormalizeAcrossScale()`. Enable this flag to analyzing an image across scale-space. In the current example, this setting has no impact because we are actually renormalizing the output to the dynamic range of the reader, so we simply disable the flag.

```
const bool normalizeAcrossScale = false;
filterX1->SetNormalizeAcrossScale(normalizeAcrossScale);
filterY1->SetNormalizeAcrossScale(normalizeAcrossScale);
filterX2->SetNormalizeAcrossScale(normalizeAcrossScale);
filterY2->SetNormalizeAcrossScale(normalizeAcrossScale);
```

The input image can be obtained from the output of another filter. Here, an image reader is used as the source. The image is passed to the x filter and then to the y filter. The reason for keeping these two filters separate is that it is usual in scale-space applications to compute not only the smoothing but also combinations of derivatives at different orders and smoothing. Some factorization is possible when separate filters are used to generate the intermediate results. Here this capability is less interesting, though, since we only want to smooth the image in all directions.

```
filterX1->SetInput(reader->GetOutput());
filterY1->SetInput(filterX1->GetOutput());

filterY2->SetInput(reader->GetOutput());
filterX2->SetInput(filterY2->GetOutput());
```

It is now time to select the σ of the Gaussian used to smooth the data. Note that σ must be passed to both filters and that sigma is considered to be in the units of the image spacing. That is, at the moment of applying the smoothing process, the filter will take into account the spacing values defined in the image.

```
filterX1->SetSigma(sigma);
filterY1->SetSigma(sigma);
filterX2->SetSigma(sigma);
filterY2->SetSigma(sigma);
```

Finally the two components of the Laplacian should be added together. The `itk::AddImageFilter` is used for this purpose.

```
typedef itk::AddImageFilter<
    OutputImageType,
    OutputImageType,
    OutputImageType> AddFilterType;
```

```
AddFilterType::Pointer addFilter = AddFilterType::New();

addFilter->SetInput1(filterY1->GetOutput());
addFilter->SetInput2(filterX2->GetOutput());
```

The filters are triggered by invoking `Update()` on the Add filter at the end of the pipeline.

```
try
  {
  addFilter->Update();
  }
catch (itk::ExceptionObject& err)
  {
  std::cout << "ExceptionObject caught !" << std::endl;
  std::cout << err << std::endl;
  return EXIT_FAILURE;
  }
```

The resulting image could be saved to a file using the `otb::ImageFileWriter` class.

```
typedef  float WritePixelType;

typedef otb::Image<WritePixelType, 2> WriteImageType;

typedef otb::ImageFileWriter<WriteImageType> WriterType;

WriterType::Pointer writer = WriterType::New();

writer->SetInput(addFilter->GetOutput());

writer->SetFileName(argv[2]);

writer->Update();
```

Figure 8.10 illustrates the effect of this filter using σ values of 3 (left) and 5 (right). The figure shows how the attenuation of noise can be regulated by selecting the appropriate standard deviation. This type of scale-tunable filter is suitable for performing scale-space analysis.

The source code for this example can be found in the file `Examples/Filtering/LaplacianRecursiveGaussianImageFilter2.cxx`.

The previous exampled showed how to use the `itk::RecursiveGaussianImageFilter` for computing the equivalent of a Laplacian of an image after smoothing with a Gaussian. The elements used in this previous example have been packaged together in the `itk::LaplacianRecursiveGaussianImageFilter` in order to simplify its usage. This current example shows how to use this convenience filter for achieving the same results as the previous example.

The first step required to use this filter is to include its header file.

```
#include "itkLaplacianRecursiveGaussianImageFilter.h"
```

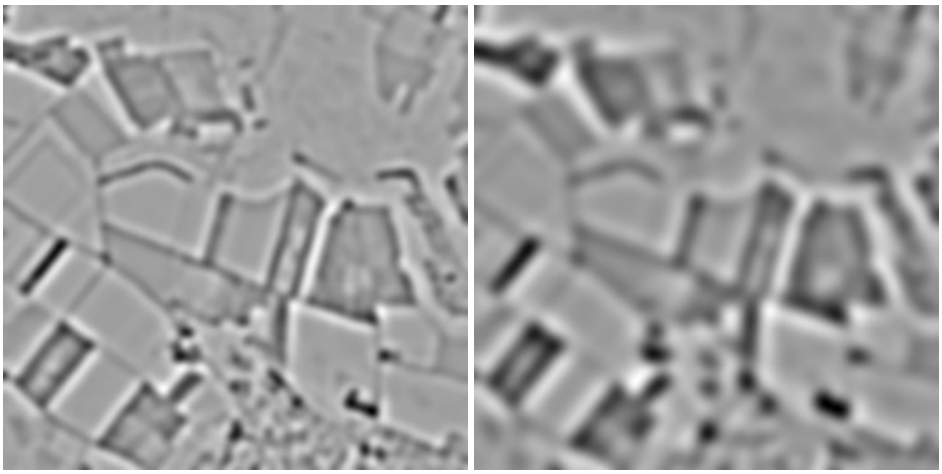


Figure 8.10: Effect of the RecursiveGaussianImageFilter.

Types should be selected on the desired input and output pixel types.

```
typedef    float InputPixelType;
typedef    float OutputPixelType;
```

The input and output image types are instantiated using the pixel types.

```
typedef otb::Image<InputPixelType,  2> InputImageType;
typedef otb::Image<OutputPixelType, 2> OutputImageType;
```

The filter type is now instantiated using both the input image and the output image types.

```
typedef itk::LaplacianRecursiveGaussianImageFilter<
    InputImageType, OutputImageType>  FilterType;
```

This filter packages all the components illustrated in the previous example. The filter is created by invoking the `New()` method and assigning the result to a `itk::SmartPointer`.

```
FilterType::Pointer laplacian = FilterType::New();
```

The option for normalizing across scale space can also be selected in this filter.

```
laplacian->SetNormalizeAcrossScale(false);
```

The input image can be obtained from the output of another filter. Here, an image reader is used as the source.

```
laplacian->SetInput(reader->GetOutput());
```

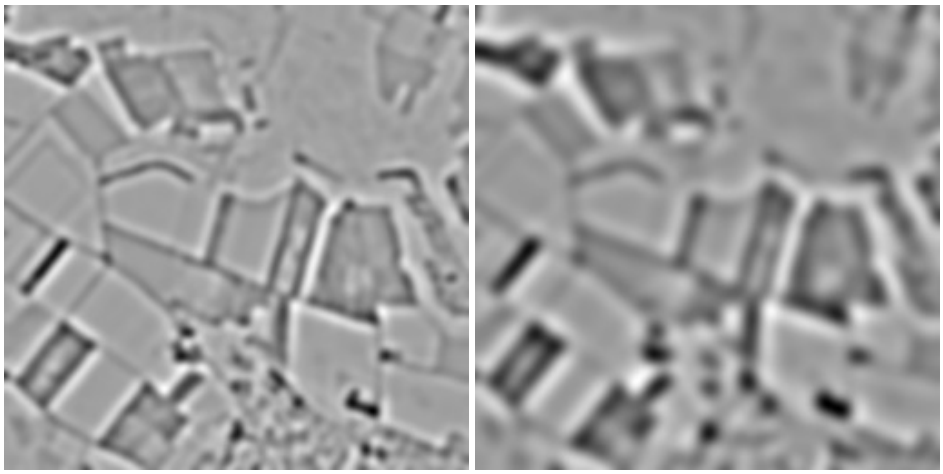


Figure 8.11: Effect of the LaplacianRecursiveGaussianImageFilter.

It is now time to select the σ of the Gaussian used to smooth the data. Note that σ must be passed to both filters and that sigma is considered to be in the units of the image spacing. That is, at the moment of applying the smoothing process, the filter will take into account the spacing values defined in the image.

```
laplacian->SetSigma(sigma);
```

Finally the pipeline is executed by invoking the `Update()` method.

```
try
  {
  laplacian->Update();
  }
catch (itk::ExceptionObject& err)
  {
  std::cout << "ExceptionObject caught !" << std::endl;
  std::cout << err << std::endl;
  return EXIT_FAILURE;
  }
```

Figure 8.11 illustrates the effect of this filter using σ values of 3 (left) and 5 (right). The figure shows how the attenuation of noise can be regulated by selecting the appropriate standard deviation. This type of scale-tunable filter is suitable for performing scale-space analysis.

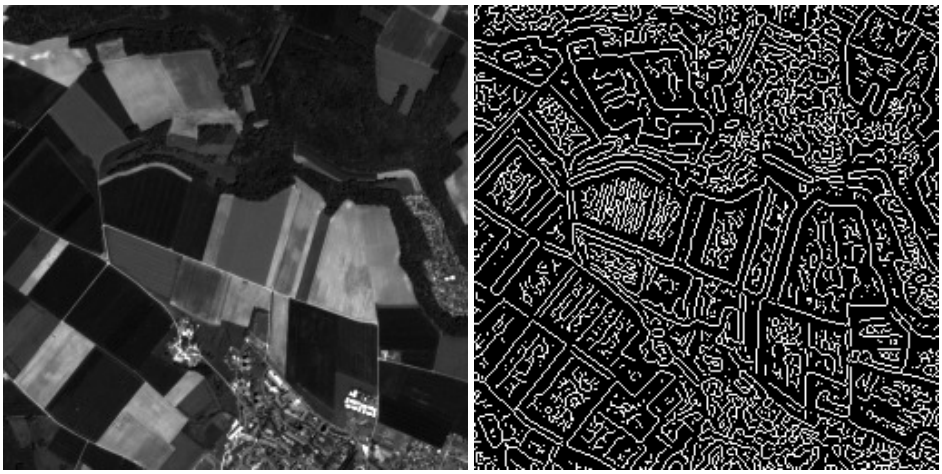


Figure 8.12: Effect of the CannyEdgeDetectorImageFilter on a ROI of a Spot 5 image.

8.5 Edge Detection

8.5.1 Canny Edge Detection

The source code for this example can be found in the file
`Examples/Filtering/CannyEdgeDetectionImageFilter.cxx`.

This example introduces the use of the `itk::CannyEdgeDetectionImageFilter`. This filter is widely used for edge detection since it is the optimal solution satisfying the constraints of good sensitivity, localization and noise robustness.

The first step required for using this filter is to include its header file

```
#include "itkCannyEdgeDetectionImageFilter.h"
```

As the Canny filter works with real values, we can instanciated the reader using an image with pixels as double. This does not imply anything on the real image coding format which will be cast into double.

```
typedef otb::ImageFileReader<RealImageType> ReaderType;
```

The `itk::CannyEdgeDetectionImageFilter` is instantiated using the float image type.

Figure 8.12 illustrates the effect of this filter on a ROI of a Spot 5 image of an agricultural area.

8.5.2 Ratio of Means Detector

The source code for this example can be found in the file
`Examples/FeatureExtraction/TouziEdgeDetectorExample.cxx`.

This example illustrates the use of the `otb::TouziEdgeDetectorImageFilter`. This filter belongs to the family of the fixed false alarm rate edge detectors but it is apropriate for SAR images, where the speckle noise is considered as multiplicative. By analogy with the classical gradient-based edge detectors which are suited to the additive noise case, this filter computes a ratio of local means in both sides of the edge [129]. In order to have a normalized response, the following computation is performed :

$$r = 1 - min\{\frac{\mu_A}{\mu_B}, \frac{\mu_B}{\mu_A}\}, \tag{8.3}$$

where μ_A and μ_B are the local means computed at both sides of the edge. In order to detect edges with any orientation, r is computed for the 4 principal directions and the maximum response is kept.

The first step required to use this filter is to include its header file.

```
#include "otbTouziEdgeDetectorImageFilter.h"
```

Then we must decide what pixel type to use for the image. We choose to make all computations with floating point precision and rescale the results between 0 and 255 in order to export PNG images.

```
typedef  float         InternalPixelType;
typedef  unsigned char OutputPixelType;
```

The images are defined using the pixel type and the dimension.

```
typedef otb::Image<InternalPixelType,  2> InternalImageType;
typedef otb::Image<OutputPixelType,  2>   OutputImageType;
```

The filter can be instantiated using the image types defined above.

```
typedef otb::TouziEdgeDetectorImageFilter<InternalImageType,
    InternalImageType> FilterType;
```

An `ImageFileReader::c`lass is also instantiated in order to read image data from a file.

```
typedef otb::ImageFileReader<InternalImageType> ReaderType;
```

An `ImageFileWriter::i`s instantiated in order to write the output image to a file.

```
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

The intensity rescaling of the results will be carried out by the `itk::RescaleIntensityImageFilter` which is templated by the input and output image types.

```
typedef itk::RescaleIntensityImageFilter<InternalImageType,
    OutputImageType> RescalerType;
```

Both the filter and the reader are created by invoking their `New()` methods and assigning the result to SmartPointers.

```
ReaderType::Pointer reader = ReaderType::New();
FilterType::Pointer filter = FilterType::New();
```

The same is done for the rescaler and the writer.

```
RescalerType::Pointer rescaler = RescalerType::New();
WriterType::Pointer   writer = WriterType::New();
```

The `itk::RescaleIntensityImageFilter` needs to know which is the minimu and maximum values of the output generated image. Those can be chosen in a generic way by using the `NumericTraits` functions, since they are templated over the pixel type.

```
rescaler->SetOutputMinimum(itk::NumericTraits<OutputPixelType>::min());
rescaler->SetOutputMaximum(itk::NumericTraits<OutputPixelType>::max());
```

The image obtained with the reader is passed as input to the `otb::TouziEdgeDetectorImageFilter`. The pipeline is built as follows.

```
filter->SetInput(reader->GetOutput());
rescaler->SetInput(filter->GetOutput());
writer->SetInput(rescaler->GetOutput());
```

The method `SetRadius()` defines the size of the window to be used for the computation of the local means.

```
FilterType::SizeType Radius;
Radius[0] = atoi(argv[4]);
Radius[1] = atoi(argv[4]);

filter->SetRadius(Radius);
```

The filter is executed by invoking the `Update()` method. If the filter is part of a larger image processing pipeline, calling `Update()` on a downstream filter will also trigger update of this filter.

```
filter->Update();
```

We can also obtain the direction of the edges by invoking the `GetOutputDirection()` method.

```
rescaler->SetInput(filter->GetOutputDirection());
writer->SetInput(rescaler->GetOutput());
writer->Update();
```

Figure 8.13 shows the result of applying the Touzi edge detector filter to a SAR image.

Figure 8.13: Result of applying the `otb::TouziEdgeDetectorImageFilter` to a SAR image. From left to right : original image, edge intensity and edge orientation.

8.6 Neighborhood Filters

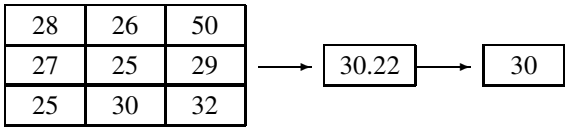
The concept of locality is frequently encountered in image processing in the form of filters that compute every output pixel using information from a small region in the neighborhood of the input pixel. The classical form of these filters are the 3×3 filters in 2D images. Convolution masks based on these neighborhoods can perform diverse tasks ranging from noise reduction, to differential operations, to mathematical morphology.

The Insight toolkit implements an elegant approach to neighborhood-based image filtering. The input image is processed using a special iterator called the `itk::NeighborhoodIterator`. This iterator is capable of moving over all the pixels in an image and, for each position, it can address the pixels in a local neighborhood. Operators are defined that apply an algorithmic operation in the neighborhood of the input pixel to produce a value for the output pixel. The following section describes some of the more commonly used filters that take advantage of this construction. (See Chapter 25 on page 561 for more information about iterators.)

8.6.1 Mean Filter

The source code for this example can be found in the file
`Examples/Filtering/MeanImageFilter.cxx`.

The `itk::MeanImageFilter` is commonly used for noise reduction. The filter computes the value of each output pixel by finding the statistical mean of the neighborhood of the corresponding input pixel. The following figure illustrates the local effect of the MeanImageFilter. The statistical mean of the neighborhood on the left is passed as the output value associated with the pixel at the center of the neighborhood.



Note that this algorithm is sensitive to the presence of outliers in the neighborhood. This filter will work on images of any dimension thanks to the internal use of `itk::SmartNeighborhoodIterator` and `itk::NeighborhoodOperator`. The size of the neighborhood over which the mean is computed can be set by the user.

The header file corresponding to this filter should be included first.

```
#include "itkMeanImageFilter.h"
```

Then the pixel types for input and output image must be defined and, with them, the image types can be instantiated.

```
typedef   unsigned char InputPixelType;
typedef   unsigned char OutputPixelType;

typedef otb::Image<InputPixelType,  2> InputImageType;
typedef otb::Image<OutputPixelType, 2> OutputImageType;
```

Using the image types it is now possible to instantiate the filter type and create the filter object.

```
typedef itk::MeanImageFilter<
    InputImageType, OutputImageType>  FilterType;

FilterType::Pointer filter = FilterType::New();
```

The size of the neighborhood is defined along every dimension by passing a `SizeType` object with the corresponding values. The value on each dimension is used as the semi-size of a rectangular box. For example, in $2D$ a size of $1,2$ will result in a 3×5 neighborhood.

```
InputImageType::SizeType indexRadius;

indexRadius[0] = 1; // radius along x
indexRadius[1] = 1; // radius along y

filter->SetRadius(indexRadius);
```

The input to the filter can be taken from any other filter, for example a reader. The output can be passed down the pipeline to other filters, for example, a writer. An update call on any downstream filter will trigger the execution of the mean filter.

```
filter->SetInput(reader->GetOutput());
writer->SetInput(filter->GetOutput());
writer->Update();
```

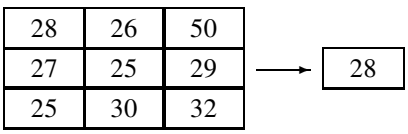
Figure 8.14: Effect of the MeanImageFilter.

Figure 8.14 illustrates the effect of this filter using neighborhood radii of $1,1$ which corresponds to a 3×3 classical neighborhood. It can be seen from this picture that edges are rapidly degraded by the diffusion of intensity values among neighbors.

8.6.2 Median Filter

The source code for this example can be found in the file
`Examples/Filtering/MedianImageFilter.cxx`.

The `itk::MedianImageFilter` is commonly used as a robust approach for noise reduction. This filter is particularly efficient against *salt-and-pepper* noise. In other words, it is robust to the presence of gray-level outliers. MedianImageFilter computes the value of each output pixel as the statistical median of the neighborhood of values around the corresponding input pixel. The following figure illustrates the local effect of this filter. The statistical median of the neighborhood on the left is passed as the output value associated with the pixel at the center of the neighborhood.



This filter will work on images of any dimension thanks to the internal use of `itk::NeighborhoodIterator` and `itk::NeighborhoodOperator`. The size of the neighborhood over which the median is computed can be set by the user.

The header file corresponding to this filter should be included first.

```
#include "itkMedianImageFilter.h"
```

Then the pixel and image types of the input and output must be defined.

```
typedef   unsigned char InputPixelType;
typedef   unsigned char OutputPixelType;

typedef otb::Image<InputPixelType,  2> InputImageType;
typedef otb::Image<OutputPixelType, 2> OutputImageType;
```

Using the image types, it is now possible to define the filter type and create the filter object.

```
typedef itk::MedianImageFilter<
    InputImageType, OutputImageType>  FilterType;

FilterType::Pointer filter = FilterType::New();
```

The size of the neighborhood is defined along every dimension by passing a `SizeType` object with the corresponding values. The value on each dimension is used as the semi-size of a rectangular box. For example, in $2D$ a size of $1,2$ will result in a 3×5 neighborhood.

```
InputImageType::SizeType indexRadius;

indexRadius[0] = 1; // radius along x
indexRadius[1] = 1; // radius along y

filter->SetRadius(indexRadius);
```

The input to the filter can be taken from any other filter, for example a reader. The output can be passed down the pipeline to other filters, for example, a writer. An update call on any downstream filter will trigger the execution of the median filter.

```
filter->SetInput(reader->GetOutput());
writer->SetInput(filter->GetOutput());
writer->Update();
```

Figure 8.15 illustrates the effect of the MedianImageFilter filter a neighborhood radius of $1,1$, which corresponds to a 3×3 classical neighborhood. The filtered image demonstrates the moderate tendency of the median filter to preserve edges.

8.6.3 Mathematical Morphology

Mathematical morphology has proved to be a powerful resource for image processing and analysis [123]. ITK implements mathematical morphology filters using NeighborhoodIterators and `itk::NeighborhoodOperators`. The toolkit contains two types of image morphology algorithms, filters that operate on binary images and filters that operate on grayscale images.

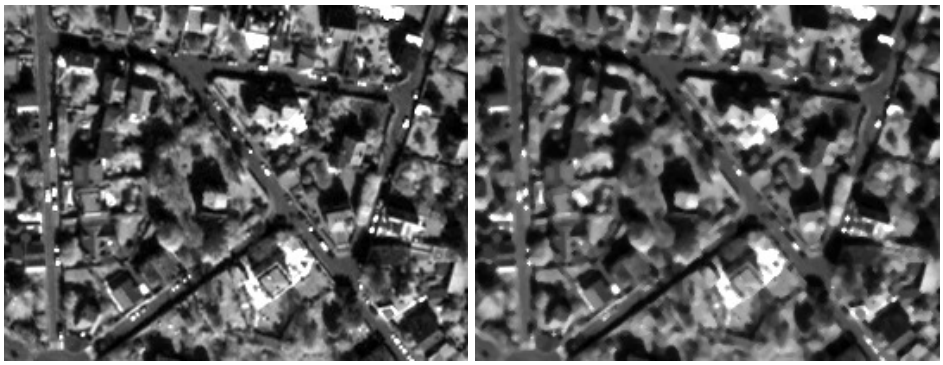


Figure 8.15: Effect of the MedianImageFilter.

Binary Filters

The source code for this example can be found in the file
`Examples/Filtering/MathematicalMorphologyBinaryFilters.cxx`.

The following section illustrates the use of filters that perform basic mathematical morphology operations on binary images. The `itk::BinaryErodeImageFilter` and `itk::BinaryDilateImageFilter` are described here. The filter names clearly specify the type of image on which they operate. The header files required to construct a simple example of the use of the mathematical morphology filters are included below.

```
#include "itkBinaryErodeImageFilter.h"
#include "itkBinaryDilateImageFilter.h"
#include "itkBinaryBallStructuringElement.h"
```

The following code defines the input and output pixel types and their associated image types.

```
  const unsigned int Dimension = 2;

  typedef unsigned char InputPixelType;
  typedef unsigned char OutputPixelType;

  typedef otb::Image<InputPixelType,  Dimension> InputImageType;
  typedef otb::Image<OutputPixelType, Dimension> OutputImageType;
```

Mathematical morphology operations are implemented by applying an operator over the neighborhood of each input pixel. The combination of the rule and the neighborhood is known as *structuring element*. Although some rules have become de facto standards for image processing, there is a good deal of freedom as to what kind of algorithmic rule should be applied to the neighborhood. The implementation in ITK follows the typical rule of minimum for erosion and maximum for dilation.

The structuring element is implemented as a NeighborhoodOperator. In particular, the default structuring element is the `itk::BinaryBallStructuringElement` class. This class is instantiated

using the pixel type and dimension of the input image.

```
typedef itk::BinaryBallStructuringElement<
    InputPixelType,
    Dimension>             StructuringElementType;
```

The structuring element type is then used along with the input and output image types for instantiating the type of the filters.

```
typedef itk::BinaryErodeImageFilter<
    InputImageType,
    OutputImageType,
    StructuringElementType>  ErodeFilterType;

typedef itk::BinaryDilateImageFilter<
    InputImageType,
    OutputImageType,
    StructuringElementType>  DilateFilterType;
```

The filters can now be created by invoking the `New()` method and assigning the result to `itk::SmartPointers`.

```
ErodeFilterType::Pointer  binaryErode  = ErodeFilterType::New();
DilateFilterType::Pointer binaryDilate = DilateFilterType::New();
```

The structuring element is not a reference counted class. Thus it is created as a C++ stack object instead of using `New()` and SmartPointers. The radius of the neighborhood associated with the structuring element is defined with the `SetRadius()` method and the `CreateStructuringElement()` method is invoked in order to initialize the operator. The resulting structuring element is passed to the mathematical morphology filter through the `SetKernel()` method, as illustrated below.

```
StructuringElementType structuringElement;

structuringElement.SetRadius(1);    // 3x3 structuring element

structuringElement.CreateStructuringElement();

binaryErode->SetKernel(structuringElement);
binaryDilate->SetKernel(structuringElement);
```

A binary image is provided as input to the filters. This image might be, for example, the output of a binary threshold image filter.

```
thresholder->SetInput(reader->GetOutput());

InputPixelType background =   0;
InputPixelType foreground = 255;

thresholder->SetOutsideValue(background);
thresholder->SetInsideValue(foreground);
```

Figure 8.16: Effect of erosion and dilation in a binary image.

```
thresholder->SetLowerThreshold(lowerThreshold);
thresholder->SetUpperThreshold(upperThreshold);
```

```
binaryErode->SetInput(thresholder->GetOutput());
binaryDilate->SetInput(thresholder->GetOutput());
```

The values that correspond to "objects" in the binary image are specified with the methods `SetErodeValue()` and `SetDilateValue()`. The value passed to these methods will be considered the value over which the dilation and erosion rules will apply.

```
binaryErode->SetErodeValue(foreground);
binaryDilate->SetDilateValue(foreground);
```

The filter is executed by invoking its `Update()` method, or by updating any downstream filter, like, for example, an image writer.

```
writerDilation->SetInput(binaryDilate->GetOutput());
writerDilation->Update();
```

Figure 8.16 illustrates the effect of the erosion and dilation filters. The figure shows how these operations can be used to remove spurious details from segmented images.

Grayscale Filters

The source code for this example can be found in the file
`Examples/Filtering/MathematicalMorphologyGrayscaleFilters.cxx`.

The following section illustrates the use of filters for performing basic mathematical morphology operations on grayscale images. The `itk::GrayscaleErodeImageFilter` and

itk::GrayscaleDilateImageFilter are covered in this example. The filter names clearly specify the type of image on which they operate. The header files required for a simple example of the use of grayscale mathematical morphology filters are presented below.

```
#include "itkGrayscaleErodeImageFilter.h"
#include "itkGrayscaleDilateImageFilter.h"
#include "itkBinaryBallStructuringElement.h"
```

The following code defines the input and output pixel types and their associated image types.

```
  const unsigned int Dimension = 2;

  typedef unsigned char InputPixelType;
  typedef unsigned char OutputPixelType;

  typedef otb::Image<InputPixelType,  Dimension> InputImageType;
  typedef otb::Image<OutputPixelType, Dimension> OutputImageType;
```

Mathematical morphology operations are based on the application of an operator over a neighborhood of each input pixel. The combination of the rule and the neighborhood is known as *structuring element*. Although some rules have become the de facto standard in image processing there is a good deal of freedom as to what kind of algorithmic rule should be applied on the neighborhood. The implementation in ITK follows the typical rule of minimum for erosion and maximum for dilation.

The structuring element is implemented as a itk::NeighborhoodOperator. In particular, the default structuring element is the itk::BinaryBallStructuringElement class. This class is instantiated using the pixel type and dimension of the input image.

```
  typedef itk::BinaryBallStructuringElement<
      InputPixelType,
      Dimension>             StructuringElementType;
```

The structuring element type is then used along with the input and output image types for instantiating the type of the filters.

```
  typedef itk::GrayscaleErodeImageFilter<
      InputImageType,
      OutputImageType,
      StructuringElementType>  ErodeFilterType;

  typedef itk::GrayscaleDilateImageFilter<
      InputImageType,
      OutputImageType,
      StructuringElementType>  DilateFilterType;
```

The filters can now be created by invoking the New() method and assigning the result to SmartPointers.

```
  ErodeFilterType::Pointer  grayscaleErode  = ErodeFilterType::New();
  DilateFilterType::Pointer grayscaleDilate = DilateFilterType::New();
```

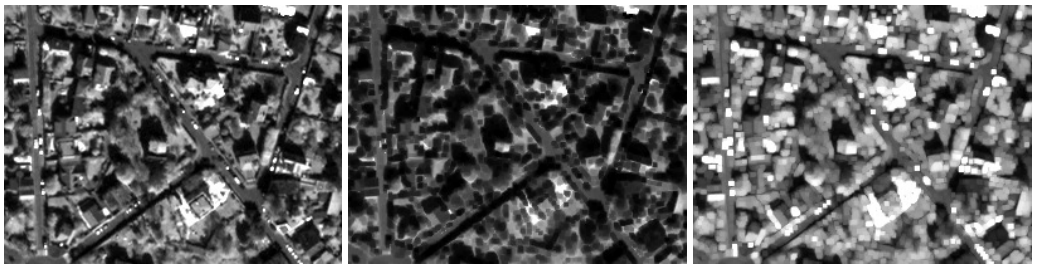


Figure 8.17: Effect of erosion and dilation in a grayscale image.

The structuring element is not a reference counted class. Thus it is created as a C++ stack object instead of using `New()` and SmartPointers. The radius of the neighborhood associated with the structuring element is defined with the `SetRadius()` method and the `CreateStructuringElement()` method is invoked in order to initialize the operator. The resulting structuring element is passed to the mathematical morphology filter through the `SetKernel()` method, as illustrated below.

```
StructuringElementType structuringElement;

structuringElement.SetRadius(1);    // 3x3 structuring element

structuringElement.CreateStructuringElement();

grayscaleErode->SetKernel(structuringElement);
grayscaleDilate->SetKernel(structuringElement);
```

A grayscale image is provided as input to the filters. This image might be, for example, the output of a reader.

```
grayscaleErode->SetInput(reader->GetOutput());
grayscaleDilate->SetInput(reader->GetOutput());
```

The filter is executed by invoking its `Update()` method, or by updating any downstream filter, like, for example, an image writer.

```
writerDilation->SetInput(grayscaleDilate->GetOutput());
writerDilation->Update();
```

Figure 8.17 illustrates the effect of the erosion and dilation filters. The figure shows how these operations can be used to remove spurious details from segmented images.

8.7 Smoothing Filters

Real image data has a level of uncertainty that is manifested in the variability of measures assigned to pixels. This uncertainty is usually interpreted as noise and considered an undesirable component

of the image data. This section describes several methods that can be applied to reduce noise on images.

8.7.1 Blurring

Blurring is the traditional approach for removing noise from images. It is usually implemented in the form of a convolution with a kernel. The effect of blurring on the image spectrum is to attenuate high spatial frequencies. Different kernels attenuate frequencies in different ways. One of the most commonly used kernels is the Gaussian. Two implementations of Gaussian smoothing are available in the toolkit. The first one is based on a traditional convolution while the other is based on the application of IIR filters that approximate the convolution with a Gaussian [36, 37].

Discrete Gaussian

The source code for this example can be found in the file `Examples/Filtering/DiscreteGaussianImageFilter.cxx`.

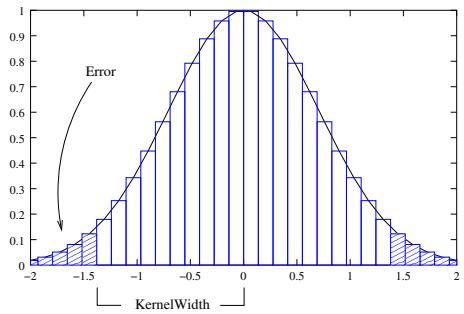


Figure 8.18: Discretized Gaussian.

The `itk::DiscreteGaussianImageFilter` computes the convolution of the input image with a Gaussian kernel. This is done in *ND* by taking advantage of the separability of the Gaussian kernel. A one-dimensional Gaussian function is discretized on a convolution kernel. The size of the kernel is extended until there are enough discrete points in the Gaussian to ensure that a user-provided maximum error is not exceeded. Since the size of the kernel is unknown a priori, it is necessary to impose a limit to its growth. The user can thus provide a value to be the maximum admissible size of the kernel. Discretization error is defined as the difference between the area under the discrete Gaussian curve (which has finite support) and the area under the continuous Gaussian.

Gaussian kernels in ITK are constructed according to the theory of Tony Lindeberg [87] so that smoothing and derivative operations commute before and after discretization. In other words, finite difference derivatives on an image I that has been smoothed by convolution with the Gaussian are equivalent to finite differences computed on I by convolving with a derivative of the Gaussian.

The first step required to use this filter is to include its header file.

```
#include "itkDiscreteGaussianImageFilter.h"
```

Types should be chosen for the pixels of the input and output images. Image types can be instantiated using the pixel type and dimension.

```
typedef    float InputPixelType;
typedef    float OutputPixelType;

typedef otb::Image<InputPixelType,  2> InputImageType;
typedef otb::Image<OutputPixelType, 2> OutputImageType;
```

The discrete Gaussian filter type is instantiated using the input and output image types. A corresponding filter object is created.

```
typedef itk::DiscreteGaussianImageFilter<
    InputImageType, OutputImageType>  FilterType;

FilterType::Pointer filter = FilterType::New();
```

The input image can be obtained from the output of another filter. Here, an image reader is used as its input.

```
filter->SetInput(reader->GetOutput());
```

The filter requires the user to provide a value for the variance associated with the Gaussian kernel. The method `SetVariance()` is used for this purpose. The discrete Gaussian is constructed as a convolution kernel. The maximum kernel size can be set by the user. Note that the combination of variance and kernel-size values may result in a truncated Gaussian kernel.

```
filter->SetVariance(gaussianVariance);
filter->SetMaximumKernelWidth(maxKernelWidth);
```

Finally, the filter is executed by invoking the `Update()` method.

```
filter->Update();
```

If the output of this filter has been connected to other filters down the pipeline, updating any of the downstream filters would have triggered the execution of this one. For example, a writer could have been used after the filter.

```
rescaler->SetInput(filter->GetOutput());
writer->SetInput(rescaler->GetOutput());
writer->Update();
```

Figure 8.19 illustrates the effect of this filter.

Note that large Gaussian variances will produce large convolution kernels and correspondingly slower computation times. Unless a high degree of accuracy is required, it may be more desirable to use the approximating `itk::RecursiveGaussianImageFilter` with large variances.

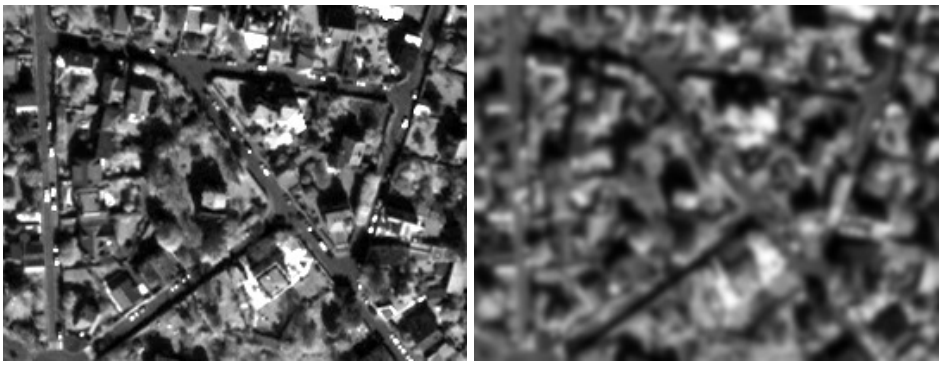


Figure 8.19: Effect of the DiscreteGaussianImageFilter.

8.7.2 Edge Preserving Smoothing

Introduction to Anisotropic Diffusion

The drawback of image denoising (smoothing) is that it tends to blur away the sharp boundaries in the image that help to distinguish between the larger-scale anatomical structures that one is trying to characterize (which also limits the size of the smoothing kernels in most applications). Even in cases where smoothing does not obliterate boundaries, it tends to distort the fine structure of the image and thereby changes subtle aspects of the anatomical shapes in question.

Perona and Malik [106] introduced an alternative to linear-filtering that they called *anisotropic diffusion*. Anisotropic diffusion is closely related to the earlier work of Grossberg [53], who used similar nonlinear diffusion processes to model human vision. The motivation for anisotropic diffusion (also called *nonuniform* or *variable conductance* diffusion) is that a Gaussian smoothed image is a single time slice of the solution to the heat equation, that has the original image as its initial conditions. Thus, the solution to

$$\frac{\partial g(x,y,t)}{\partial t} = \nabla \cdot \nabla g(x,y,t), \tag{8.4}$$

where $g(x,y,0) = f(x,y)$ is the input image, is $g(x,y,t) = G(\sqrt{2t}) \otimes f(x,y)$, where $G(\sigma)$ is a Gaussian with standard deviation σ.

Anisotropic diffusion includes a variable conductance term that, in turn, depends on the differential structure of the image. Thus, the variable conductance can be formulated to limit the smoothing at "edges" in images, as measured by high gradient magnitude, for example.

$$g_t = \nabla \cdot c(|\nabla g|)\nabla g, \tag{8.5}$$

where, for notational convenience, we leave off the independent parameters of g and use the subscripts with respect to those parameters to indicate partial derivatives. The function $c(|\nabla g|)$ is a fuzzy cutoff that reduces the conductance at areas of large $|\nabla g|$, and can be any one of a number of

functions. The literature has shown

$$c(|\nabla g|) = e^{-\frac{|\nabla g|^2}{2k^2}} \tag{8.6}$$

to be quite effective. Notice that conductance term introduces a free parameter k, the *conductance parameter*, that controls the sensitivity of the process to edge contrast. Thus, anisotropic diffusion entails two free parameters: the conductance parameter, k, and the time parameter, t, that is analogous to σ, the effective width of the filter when using Gaussian kernels.

Equation 8.5 is a nonlinear partial differential equation that can be solved on a discrete grid using finite forward differences. Thus, the smoothed image is obtained only by an iterative process, not a convolution or non-stationary, linear filter. Typically, the number of iterations required for practical results are small, and large 2D images can be processed in several tens of seconds using carefully written code running on modern, general purpose, single-processor computers. The technique applies readily and effectively to 3D images, but requires more processing time.

In the early 1990's several research groups [49, 137] demonstrated the effectiveness of anisotropic diffusion on medical images. In a series of papers on the subject [142, 139, 141, 137, 138, 140], Whitaker described a detailed analytical and empirical analysis, introduced a smoothing term in the conductance that made the process more robust, invented a numerical scheme that virtually eliminated directional artifacts in the original algorithm, and generalized anisotropic diffusion to vector-valued images, an image processing technique that can be used on vector-valued medical data (such as the color cryosection data of the Visible Human Project).

For a vector-valued input $\vec{F} : U \mapsto \Re^m$ the process takes the form

$$\vec{F}_t = \nabla \cdot c(\mathcal{D}\vec{F})\vec{F}, \tag{8.7}$$

where $\mathcal{D}\vec{F}$ is a *dissimilarity* measure of $\vec{F}$, a generalization of the gradient magnitude to vector-valued images, that can incorporate linear and nonlinear coordinate transformations on the range of $\vec{F}$. In this way, the smoothing of the multiple images associated with vector-valued data is coupled through the conductance term, that fuses the information in the different images. Thus vector-valued, nonlinear diffusion can combine low-level image features (e.g. edges) across all "channels" of a vector-valued image in order to preserve or enhance those features in all of image "channels".

Vector-valued anisotropic diffusion is useful for denoising data from devices that produce multiple values such as MRI or color photography. When performing nonlinear diffusion on a color image, the color channels are diffused separately, but linked through the conductance term. Vector-valued diffusion it is also useful for processing registered data from different devices or for denoising higher-order geometric or statistical features from scalar-valued images [140, 149].

The output of anisotropic diffusion is an image or set of images that demonstrates reduced noise and texture but preserves, and can also enhance, edges. Such images are useful for a variety of processes including statistical classification, visualization, and geometric feature extraction. Previous work has shown [138] that anisotropic diffusion, over a wide range of conductance parameters, offers quantifiable advantages over linear filtering for edge detection in medical images.

Since the effectiveness of nonlinear diffusion was first demonstrated, numerous variations of this approach have surfaced in the literature [128]. These include alternatives for constructing dissimilarity

measures [121], directional (i.e., tensor-valued) conductance terms [135, 6] and level set interpretations [143].

Gradient Anisotropic Diffusion

The source code for this example can be found in the file
`Examples/Filtering/GradientAnisotropicDiffusionImageFilter.cxx`.

The `itk::GradientAnisotropicDiffusionImageFilter` implements an N-dimensional version of the classic Perona-Malik anisotropic diffusion equation for scalar-valued images [106].

The conductance term for this implementation is chosen as a function of the gradient magnitude of the image at each point, reducing the strength of diffusion at edge pixels.

$$C(\mathbf{x}) = e^{-(\frac{\|\nabla U(\mathbf{x})\|}{K})^2} \tag{8.8}$$

The numerical implementation of this equation is similar to that described in the Perona-Malik paper [106], but uses a more robust technique for gradient magnitude estimation and has been generalized to N-dimensions.

The first step required to use this filter is to include its header file.

```
#include "itkGradientAnisotropicDiffusionImageFilter.h"
```

Types should be selected based on the pixel types required for the input and output images. The image types are defined using the pixel type and the dimension.

```
typedef    float InputPixelType;
typedef    float OutputPixelType;

typedef otb::Image<InputPixelType,  2> InputImageType;
typedef otb::Image<OutputPixelType, 2> OutputImageType;
```

The filter type is now instantiated using both the input image and the output image types. The filter object is created by the `New()` method.

```
typedef itk::GradientAnisotropicDiffusionImageFilter<
    InputImageType, OutputImageType>  FilterType;
FilterType::Pointer filter = FilterType::New();
```

The input image can be obtained from the output of another filter. Here, an image reader is used as source.

```
filter->SetInput(reader->GetOutput());
```

This filter requires three parameters, the number of iterations to be performed, the time step and the conductance parameter used in the computation of the level set evolution.

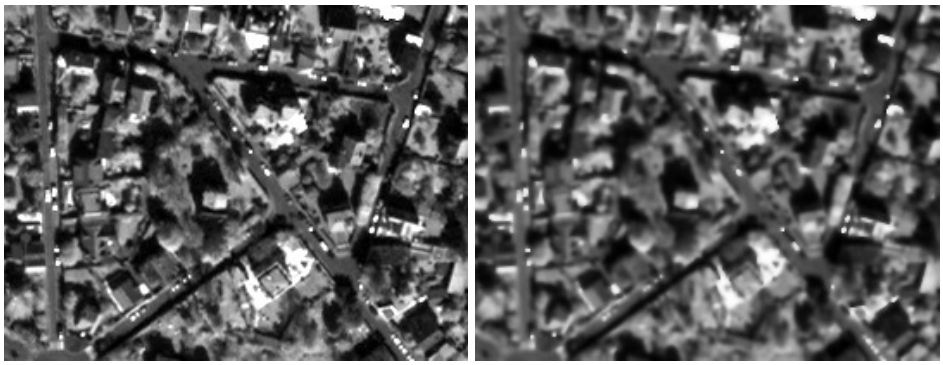


Figure 8.20: Effect of the GradientAnisotropicDiffusionImageFilter.

These parameters are set using the methods `SetNumberOfIterations()`, `SetTimeStep()` and `SetConductanceParameter()` respectively. The filter can be executed by invoking Update().

```
filter->SetNumberOfIterations(numberOfIterations);
filter->SetTimeStep(timeStep);
filter->SetConductanceParameter(conductance);

filter->Update();
```

A typical value for the time step is 0.125. The number of iterations is typically set to 5; more iterations result in further smoothing and will increase the computing time linearly.

Figure 8.20 illustrates the effect of this filter. In this example the filter was run with a time step of 0.125, and 5 iterations. The figure shows how homogeneous regions are smoothed and edges are preserved.

The following classes provide similar functionality:

- `itk::BilateralImageFilter`
- `itk::CurvatureAnisotropicDiffusionImageFilter`
- `itk::CurvatureFlowImageFilter`

Mean Shift filtering and clustering

The source code for this example can be found in the file
`Examples/BasicFilters/MeanShiftSegmentationFilterExample.cxx`.

This example demonstrates the use of the `otb::MeanShiftSegmentationFilter` class which implements filtering and clustering using the mean shift algorithm [29]. For a given pixel, the

mean shift will build a set of neighboring pixels within a given spatial radius and a color range. The spatial and color center of this set is then computed and the algorithm iterates with this new spatial and color center. The Mean Shift can be used for edge-preserving smoothing, or for clustering.

We start by including the needed header file.

```
#include "otbMeanShiftSegmentationFilter.h"
```

We start by the classical typedefs needed for reading and writing the images.

```
const unsigned int Dimension = 2;

typedef float                         PixelType;
typedef unsigned int                  LabelPixelType;
typedef itk::RGBPixel<unsigned char> ColorPixelType;

typedef otb::VectorImage<PixelType, Dimension> ImageType;
typedef otb::Image<LabelPixelType, Dimension>  LabelImageType;
typedef otb::Image<ColorPixelType, Dimension>  RGBImageType;

typedef otb::ImageFileReader<ImageType>               ReaderType;
typedef otb::ImageFileWriter<ImageType>      WriterType;
typedef otb::ImageFileWriter<LabelImageType> LabelWriterType;

typedef otb::MeanShiftSegmentationFilter<ImageType, LabelImageType, ImageType> FilterType;
```

We instantiate the filter, the reader, and 2 writers (for the labeled and clustered images).

```
FilterType::Pointer filter = FilterType::New();
ReaderType::Pointer reader = ReaderType::New();
WriterType::Pointer writer1 = WriterType::New();
LabelWriterType::Pointer writer2 = LabelWriterType::New();
```

We set the file names for the reader and the writers:

```
reader->SetFileName(infname);
writer1->SetFileName(clusteredfname);
writer2->SetFileName(labeledfname);
```

We can now set the parameters for the filter. There are 3 main parameters: the spatial radius used for defining the neighborhood, the range radius used for defining the interval in the color space and the minimum size for the regions to be kept after clustering.

```
filter->SetSpatialBandwidth(spatialRadius);
filter->SetRangeBandwidth(rangeRadius);
filter->SetMinRegionSize(minRegionSize);
```

Two another parameters can be set : the maximum iteration number, which defines maximum number of iteration until convergence. Algorithm iterative scheme will stop if convergence hasn't been reached after the maximum number of iterations. Threshold parameter defines mean-shift vector convergence value. Algorithm iterative scheme will stop if mean-shift vector is below this threshold or if iteration number reached maximum number of iterations.

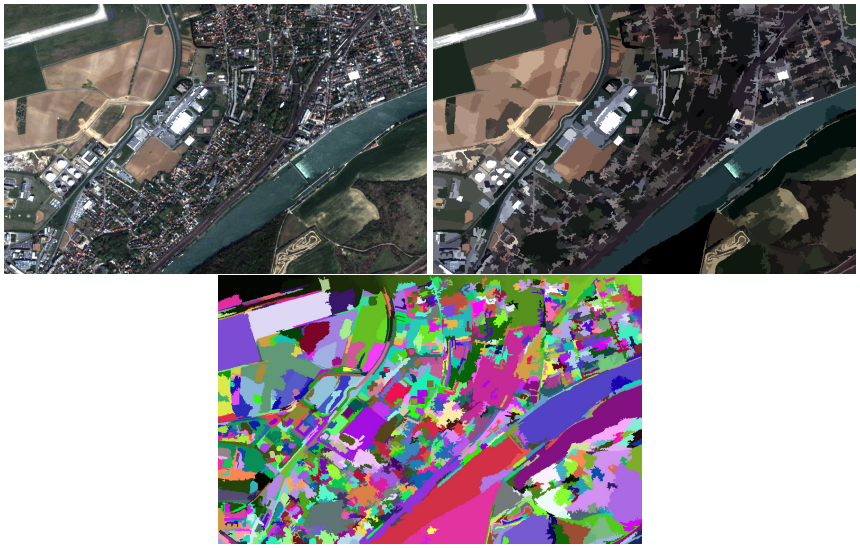


Figure 8.21: From top to bottom and left to right: Original image, image filtered by mean shift after clustering , and labeled image.

```
filter->SetMaxIterationNumber(maxiter);
filter->SetThreshold(thres);
```

We can now plug the pipeline and run it.

```
filter->SetInput(reader->GetOutput());
writer1->SetInput(filter->GetClusteredOutput());
writer2->SetInput(filter->GetLabelOutput());

writer1->Update();
writer2->Update();
```

Figure 8.21 shows the result of applying the mean shift to a Quickbird image.

8.7.3 Edge Preserving Speckle Reduction Filters

The source code for this example can be found in the file
`Examples/BasicFilters/LeeImageFilter.cxx`.

This example illustrates the use of the `otb::LeeImageFilter`. This filter belongs to the family of the edge-preserving smoothing filters which are usually used for speckle reduction in radar images. The Lee filter [84] aplies a linear regression which minimizes the mean-square error in the frame of a multiplicative speckle model.

The first step required to use this filter is to include its header file.

```
#include "otbLeeImageFilter.h"
```

Then we must decide what pixel type to use for the image.

```
typedef  unsigned char PixelType;
```

The images are defined using the pixel type and the dimension.

```
typedef otb::Image<PixelType,  2> InputImageType;
typedef otb::Image<PixelType,  2> OutputImageType;
```

The filter can be instantiated using the image types defined above.

```
typedef otb::LeeImageFilter<InputImageType, OutputImageType> FilterType;
```

An `otb::ImageFileReader` class is also instantiated in order to read image data from a file.

```
typedef otb::ImageFileReader<InputImageType> ReaderType;
```

An `otb::ImageFileWriter` is instantiated in order to write the output image to a file.

```
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

Both the filter and the reader are created by invoking their `New()` methods and assigning the result to SmartPointers.

```
ReaderType::Pointer reader = ReaderType::New();
FilterType::Pointer filter = FilterType::New();
```

The image obtained with the reader is passed as input to the `otb::LeeImageFilter`.

```
filter->SetInput(reader->GetOutput());
```

The method `SetRadius()` defines the size of the window to be used for the computation of the local statistics. The method `SetNbLooks()` sets the number of looks of the input image.

```
FilterType::SizeType Radius;
Radius[0] = atoi(argv[3]);
Radius[1] = atoi(argv[3]);

filter->SetRadius(Radius);
filter->SetNbLooks(atoi(argv[4]));
```

Figure 8.22 shows the result of applying the Lee filter to a SAR image.

The following classes provide similar functionality:

- `otb::FrostImageFilter`

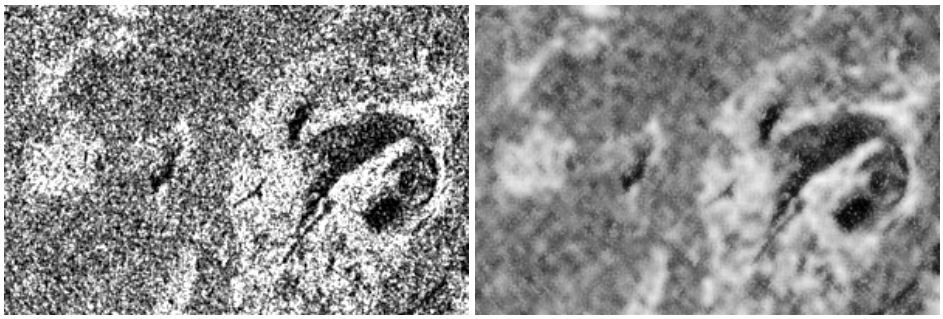


Figure 8.22: Result of applying the `otb::LeeImageFilter` to a SAR image.

The source code for this example can be found in the file
`Examples/BasicFilters/FrostImageFilter.cxx`.

This example illustrates the use of the `otb::FrostImageFilter`. This filter belongs to the family of the edge-preserving smoothing filters which are usually used for speckle reduction in radar images.

This filter uses a negative exponential convolution kernel. The output of the filter for pixel p is: $\hat{I}_s = \sum_{p \in \eta_p} m_p I_p$

where : $m_p = \frac{KC_s^2 \exp(-KC_s^2 d_{s,p})}{\sum_{p \in \eta_p} KC_s^2 \exp(-KC_s^2 d_{s,p})}$ and $d_{s,p} = \sqrt{(i-i_p)^2 + (j-j_p)^2}$

- K : the decrease coefficient
- (i, j) : the coordinates of the pixel inside the region defined by η_s
- (i_p, j_p) : the coordinates of the pixels belonging to $\eta_p \subset \eta_s$
- C_s : the variation coefficient computed over η_p

Most of this example is similar to the previous one and only the differences will be highlighted.

First, we need to include the header:

```
#include "otbFrostImageFilter.h"
```

The filter can be instantiated using the image types defined previously.

```
  typedef otb::FrostImageFilter<InputImageType, OutputImageType> FilterType;
```

The image obtained with the reader is passed as input to the `otb::FrostImageFilter`.

```
  filter->SetInput(reader->GetOutput());
```

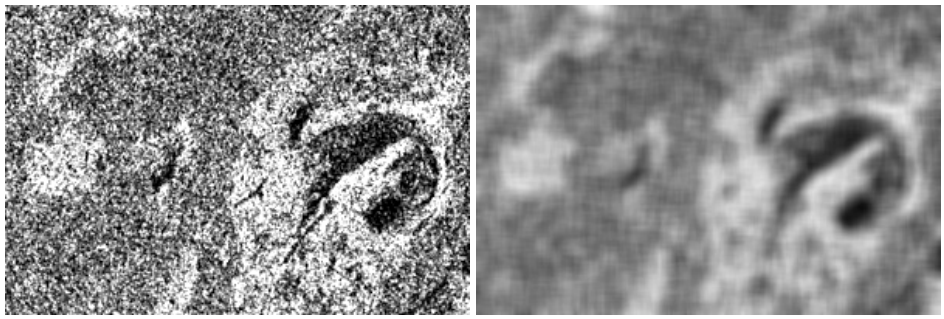


Figure 8.23: Result of applying the `otb::FrostImageFilter` to a SAR image.

The method `SetRadius()` defines the size of the window to be used for the computation of the local statistics. The method `SetDeramp()` sets the K coefficient.

```
FilterType::SizeType Radius;
Radius[0] = atoi(argv[3]);
Radius[1] = atoi(argv[3]);

filter->SetRadius(Radius);
filter->SetDeramp(atof(argv[4]));
```

Figure 8.23 shows the result of applying the Frost filter to a SAR image.

The following classes provide similar functionality:

- `otb::LeeImageFilter`

8.7.4 Edge preserving Markov Random Field

The Markov Random Field framework for OTB is more detailled in 19.2.6 (p. 471).

The source code for this example can be found in the file `Examples/Markov/MarkovRestaurationExample.cxx`.

The Markov Random Field framework can be used to apply an edge preserving filtering, thus playing a role of restauration.

This example applies the `otb::MarkovRandomFieldFilter` for image restauration. The structure of the example is similar to the other MRF example. The original image is assumed to be coded in one byte, thus 256 states are possible for each pixel. The only other modifications reside in the energy function chosen for the fidelity and for the regularization.

For the regularization energy function, we choose an edge preserving function:

$$\Phi(u) = \frac{u^2}{1+u^2} \tag{8.9}$$

and for the fidelity function, we choose a gaussian model.

The starting state of the Markov Random Field is given by the image itself as the final state should not be too far from it.

The first step toward the use of this filter is the inclusion of the proper header files:

```
#include "otbMRFEnergyEdgeFidelity.h"
#include "otbMRFEnergyGaussian.h"
#include "otbMRFOptimizerMetropolis.h"
#include "otbMRFSamplerRandom.h"
```

We declare the usual types:

```
  const unsigned int Dimension = 2;

  typedef double                                    InternalPixelType;
  typedef unsigned char                             LabelledPixelType;
  typedef otb::Image<InternalPixelType, Dimension> InputImageType;
  typedef otb::Image<LabelledPixelType, Dimension> LabelledImageType;
```

We need to declare an additional reader for the initial state of the MRF. This reader has to be instantiated on the LabelledImageType.

```
  typedef otb::ImageFileReader<InputImageType>    ReaderType;
  typedef otb::ImageFileReader<LabelledImageType> ReaderLabelledType;
  typedef otb::ImageFileWriter<LabelledImageType> WriterType;

  ReaderType::Pointer         reader = ReaderType::New();
  ReaderLabelledType::Pointer reader2 = ReaderLabelledType::New();
  WriterType::Pointer         writer = WriterType::New();

  const char * inputFilename  = argv[1];
  const char * labelledFilename  = argv[2];
  const char * outputFilename = argv[3];

  reader->SetFileName(inputFilename);
  reader2->SetFileName(labelledFilename);
  writer->SetFileName(outputFilename);
```

We declare all the necessary types for the MRF:

```
  typedef otb::MarkovRandomFieldFilter
  <InputImageType, LabelledImageType> MarkovRandomFieldFilterType;

  typedef otb::MRFSamplerRandom<InputImageType, LabelledImageType> SamplerType;

  typedef otb::MRFOptimizerMetropolis OptimizerType;
```

The regularization and the fidelity energy are declared and instanciated:

```
typedef otb::MRFEnergyEdgeFidelity
<LabelledImageType, LabelledImageType>  EnergyRegularizationType;
typedef otb::MRFEnergyGaussian
<InputImageType, LabelledImageType>  EnergyFidelityType;
```

```
MarkovRandomFieldFilterType::Pointer markovFilter =
  MarkovRandomFieldFilterType::New();

EnergyRegularizationType::Pointer energyRegularization =
  EnergyRegularizationType::New();
EnergyFidelityType::Pointer energyFidelity = EnergyFidelityType::New();

OptimizerType::Pointer optimizer = OptimizerType::New();
SamplerType::Pointer   sampler = SamplerType::New();
```

The number of possible states for each pixel is 256 as the image is assumed to be coded on one byte and we pass the parameters to the markovFilter.

```
unsigned int nClass = 256;

optimizer->SetSingleParameter(atof(argv[6]));
markovFilter->SetNumberOfClasses(nClass);
markovFilter->SetMaximumNumberOfIterations(atoi(argv[5]));
markovFilter->SetErrorTolerance(0.0);
markovFilter->SetLambda(atof(argv[4]));
markovFilter->SetNeighborhoodRadius(1);

markovFilter->SetEnergyRegularization(energyRegularization);
markovFilter->SetEnergyFidelity(energyFidelity);
markovFilter->SetOptimizer(optimizer);
markovFilter->SetSampler(sampler);
```

The original state of the MRF filter is passed through the `SetTrainingInput()` method:

```
markovFilter->SetTrainingInput(reader2->GetOutput());
```

And we plug the pipeline:

```
markovFilter->SetInput(reader->GetOutput());

typedef itk::RescaleIntensityImageFilter
<LabelledImageType, LabelledImageType> RescaleType;
RescaleType::Pointer rescaleFilter = RescaleType::New();
rescaleFilter->SetOutputMinimum(0);
rescaleFilter->SetOutputMaximum(255);

rescaleFilter->SetInput(markovFilter->GetOutput());

writer->SetInput(rescaleFilter->GetOutput());

writer->Update();
```

Figure 8.24: Result of applying the `otb::MarkovRandomFieldFilter` to an extract from a PAN Quickbird image for restauration. From left to right : original image, restaured image with edge preservation.

Figure 8.24 shows the output of the Markov Random Field restauration.

8.8 Distance Map

The source code for this example can be found in the file
`Examples/Filtering/DanielssonDistanceMapImageFilter.cxx`.

This example illustrates the use of the `itk::DanielssonDistanceMapImageFilter`. This filter generates a distance map from the input image using the algorithm developed by Danielsson [32]. As secondary outputs, a Voronoi partition of the input elements is produced, as well as a vector image with the components of the distance vector to the closest point. The input to the map is assumed to be a set of points on the input image. Each point/pixel is considered to be a separate entity even if they share the same gray level value.

The first step required to use this filter is to include its header file.

```
#include "itkConnectedComponentImageFilter.h"
#include "itkDanielssonDistanceMapImageFilter.h"
```

Then we must decide what pixel types to use for the input and output images. Since the output will contain distances measured in pixels, the pixel type should be able to represent at least the width of the image, or said in $N-D$ terms, the maximum extension along all the dimensions. The input and output image types are now defined using their respective pixel type and dimension.

```
  typedef  unsigned char                 InputPixelType;
  typedef  unsigned short                OutputPixelType;
  typedef otb::Image<InputPixelType,  2> InputImageType;
  typedef otb::Image<OutputPixelType, 2> OutputImageType;
```

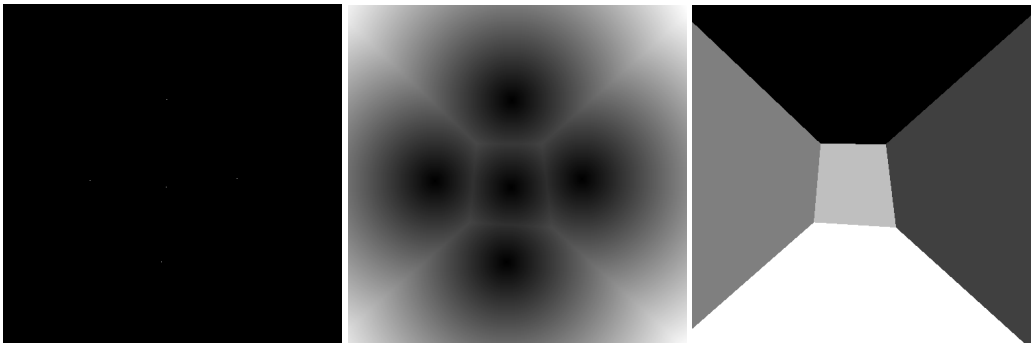


Figure 8.25: DanielssonDistanceMapImageFilter output. Set of pixels, distance map and Voronoi partition.

The filter type can be instantiated using the input and output image types defined above. A filter object is created with the `New()` method.

```
typedef itk::ConnectedComponentImageFilter<
  InputImageType, InputImageType> ConnectedType;
ConnectedType::Pointer connectedComponents = ConnectedType::New();

typedef itk::DanielssonDistanceMapImageFilter<
  InputImageType, OutputImageType, OutputImageType> FilterType;
FilterType::Pointer filter = FilterType::New();
```

The input to the filter is taken from a reader and its output is passed to a `itk::RescaleIntensityImageFilter` and then to a writer.

```
connectedComponents->SetInput(reader->GetOutput());
filter->SetInput(connectedComponents->GetOutput());
scaler->SetInput(filter->GetOutput());
writer->SetInput(scaler->GetOutput());
```

The type of input image has to be specified. In this case, a binary image is selected.

```
filter->InputIsBinaryOff();
```

Figure 8.25 illustrates the effect of this filter on a binary image with a set of points. The input image is shown at left, the distance map at the center and the Voronoi partition at right. This filter computes distance maps in N-dimensions and is therefore capable of producing $N-D$ Voronoi partitions.

The Voronoi map is obtained with the `GetVoronoiMap()` method. In the lines below we connect this output to the intensity rescaler and save the result in a file.

```
scaler->SetInput(filter->GetVoronoiMap());
writer->SetFileName(voronoiMapFileName);
writer->Update();
```

Execution of the writer is triggered by the invocation of the `Update()` method. Since this method can potentially throw exceptions it must be placed in a `try/catch` block.

CHAPTER

NINE

IMAGE REGISTRATION

This chapter introduces OTB's (actually mainly ITK's) capabilities for performing image registration. Please note that the disparity map estimation approach presented in chapter 10 are very closely related to image registration. Image registration is the process of determining the spatial transform that maps points from one image to homologous points on a object in the second image. This concept is schematically represented in Figure 9.1. In OTB, registration is performed within a framework of pluggable components that can easily be interchanged. This flexibility means that a combinatorial variety of registration methods can be created, allowing users to pick and choose the right tools for their specific application.

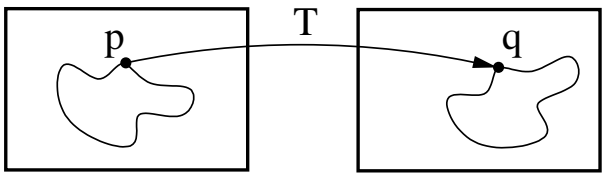


Figure 9.1: Image registration is the task of finding a spatial transform mapping on image into another.

9.1 Registration Framework

The components of the registration framework and their interconnections are shown in Figure 9.2. The basic input data to the registration process are two images: one is defined as the *fixed* image $f(\mathbf{X})$ and the other as the *moving* image $m(\mathbf{X})$. Where $\mathbf{X}$ represents a position in N-dimensional space. Registration is treated as an optimization problem with the goal of finding the spatial mapping that will bring the moving image into alignment with the fixed image.

The *transform* component $T(\mathbf{X})$ represents the spatial mapping of points from the fixed image space to points in the moving image space. The *interpolator* is used to evaluate moving image intensities at non-grid positions. The *metric* component $S(f, m \circ T)$ provides a measure of how well the fixed image is matched by the transformed moving image. This measure forms the quantitative criterion to be optimized by the *optimizer* over the search space defined by the parameters of the *transform*.

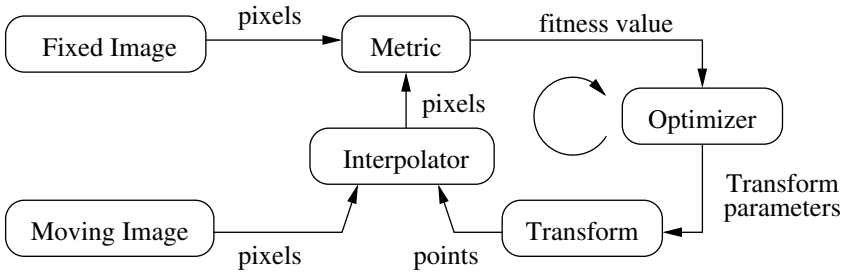


Figure 9.2: The basic components of the registration framework are two input images, a transform, a metric, an interpolator and an optimizer.

These various OTB/ITK registration components will be described in later sections. First, we begin with some simple registration examples.

9.2 ”Hello World” Registration

The source code for this example can be found in the file
`Examples/Registration/ImageRegistration1.cxx`.

This example illustrates the use of the image registration framework in ITK/OTB. It should be read as a ”Hello World” for registration. Which means that for now, you don’t ask “why?”. Instead, use the example as an introduction to the elements that are typically involved in solving an image registration problem.

A registration method requires the following set of components: two input images, a transform, a metric, an interpolator and an optimizer. Some of these components are parameterized by the image type for which the registration is intended. The following header files provide declarations of common types used for these components.

```
#include "itkImageRegistrationMethod.h"
#include "itkTranslationTransform.h"
#include "itkMeanSquaresImageToImageMetric.h"
#include "itkLinearInterpolateImageFunction.h"
#include "itkRegularStepGradientDescentOptimizer.h"
#include "otbImage.h"
```

The types of each one of the components in the registration methods should be instantiated first. With that purpose, we start by selecting the image dimension and the type used for representing image pixels.

```
  const unsigned int Dimension = 2;
  typedef  float PixelType;
```

The types of the input images are instantiated by the following lines.

```
typedef otb::Image<PixelType, Dimension> FixedImageType;
typedef otb::Image<PixelType, Dimension> MovingImageType;
```

The transform that will map the fixed image space into the moving image space is defined below.

```
typedef itk::TranslationTransform<double, Dimension> TransformType;
```

An optimizer is required to explore the parameter space of the transform in search of optimal values of the metric.

```
typedef itk::RegularStepGradientDescentOptimizer OptimizerType;
```

The metric will compare how well the two images match each other. Metric types are usually parameterized by the image types as it can be seen in the following type declaration.

```
typedef itk::MeanSquaresImageToImageMetric<
    FixedImageType,
    MovingImageType>    MetricType;
```

Finally, the type of the interpolator is declared. The interpolator will evaluate the intensities of the moving image at non-grid positions.

```
typedef itk::LinearInterpolateImageFunction<
    MovingImageType,
    double>    InterpolatorType;
```

The registration method type is instantiated using the types of the fixed and moving images. This class is responsible for interconnecting all the components that we have described so far.

```
typedef itk::ImageRegistrationMethod<
    FixedImageType,
    MovingImageType>    RegistrationType;
```

Each one of the registration components is created using its `New()` method and is assigned to its respective `itk::SmartPointer`.

```
MetricType::Pointer       metric        = MetricType::New();
TransformType::Pointer    transform     = TransformType::New();
OptimizerType::Pointer    optimizer     = OptimizerType::New();
InterpolatorType::Pointer interpolator  = InterpolatorType::New();
RegistrationType::Pointer registration  = RegistrationType::New();
```

Each component is now connected to the instance of the registration method.

```
registration->SetMetric(metric);
registration->SetOptimizer(optimizer);
registration->SetTransform(transform);
registration->SetInterpolator(interpolator);
```

Since we are working with high resolution images and expected shifts are larger than the resolution, we will need to smooth the images in order to avoid the optimizer to get stucked on local minima. In order to do this, we will use a simple mean filter.

```
typedef itk::MeanImageFilter<
    FixedImageType, FixedImageType>  FixedFilterType;

typedef itk::MeanImageFilter<
    MovingImageType, MovingImageType>  MovingFilterType;

FixedFilterType::Pointer  fixedFilter  = FixedFilterType::New();
MovingFilterType::Pointer movingFilter = MovingFilterType::New();

FixedImageType::SizeType indexFRadius;

indexFRadius[0] = 4; // radius along x
indexFRadius[1] = 4; // radius along y

fixedFilter->SetRadius(indexFRadius);

MovingImageType::SizeType indexMRadius;

indexMRadius[0] = 4; // radius along x
indexMRadius[1] = 4; // radius along y

movingFilter->SetRadius(indexMRadius);

fixedFilter->SetInput(fixedImageReader->GetOutput());
movingFilter->SetInput(movingImageReader->GetOutput());
```

Now we can plug the output of the smoothing filters at the input of the registration method.

```
registration->SetFixedImage(fixedFilter->GetOutput());
registration->SetMovingImage(movingFilter->GetOutput());
```

The registration can be restricted to consider only a particular region of the fixed image as input to the metric computation. This region is defined with the `SetFixedImageRegion()` method. You could use this feature to reduce the computational time of the registration or to avoid unwanted objects present in the image from affecting the registration outcome. In this example we use the full available content of the image. This region is identified by the `BufferedRegion` of the fixed image. Note that for this region to be valid the reader must first invoke its `Update()` method.

```
fixedFilter->Update();
registration->SetFixedImageRegion(
  fixedFilter->GetOutput()->GetBufferedRegion());
```

The parameters of the transform are initialized by passing them in an array. This can be used to setup an initial known correction of the misalignment. In this particular case, a translation transform is being used for the registration. The array of parameters for this transform is simply composed of the translation values along each dimension. Setting the values of the parameters to zero initializes the

transform to an *Identity* transform. Note that the array constructor requires the number of elements to be passed as an argument.

```
typedef RegistrationType::ParametersType ParametersType;
ParametersType initialParameters(transform->GetNumberOfParameters());

initialParameters[0] = 0.0;  // Initial offset in mm along X
initialParameters[1] = 0.0;  // Initial offset in mm along Y

registration->SetInitialTransformParameters(initialParameters);
```

At this point the registration method is ready for execution. The optimizer is the component that drives the execution of the registration. However, the ImageRegistrationMethod class orchestrates the ensemble to make sure that everything is in place before control is passed to the optimizer.

It is usually desirable to fine tune the parameters of the optimizer. Each optimizer has particular parameters that must be interpreted in the context of the optimization strategy it implements. The optimizer used in this example is a variant of gradient descent that attempts to prevent it from taking steps that are too large. At each iteration, this optimizer will take a step along the direction of the `itk::ImageToImageMetric` derivative. The initial length of the step is defined by the user. Each time the direction of the derivative abruptly changes, the optimizer assumes that a local extrema has been passed and reacts by reducing the step length by a half. After several reductions of the step length, the optimizer may be moving in a very restricted area of the transform parameter space. The user can define how small the step length should be to consider convergence to have been reached. This is equivalent to defining the precision with which the final transform should be known.

The initial step length is defined with the method `SetMaximumStepLength()`, while the tolerance for convergence is defined with the method `SetMinimumStepLength()`.

```
optimizer->SetMaximumStepLength(3);
optimizer->SetMinimumStepLength(0.01);
```

In case the optimizer never succeeds reaching the desired precision tolerance, it is prudent to establish a limit on the number of iterations to be performed. This maximum number is defined with the method `SetNumberOfIterations()`.

```
optimizer->SetNumberOfIterations(200);
```

The registration process is triggered by an invocation to the `Update()` method. If something goes wrong during the initialization or execution of the registration an exception will be thrown. We should therefore place the `Update()` method inside a `try/catch` block as illustrated in the following lines.

```
try
  {
  registration->Update();
  }
catch (itk::ExceptionObject& err)
  {
```

```
    std::cerr << "ExceptionObject caught !" << std::endl;
    std::cerr << err << std::endl;
    return -1;
    }
```

In a real life application, you may attempt to recover from the error by taking more effective actions in the catch block. Here we are simply printing out a message and then terminating the execution of the program.

The result of the registration process is an array of parameters that defines the spatial transformation in an unique way. This final result is obtained using the `GetLastTransformParameters()` method.

```
ParametersType finalParameters = registration->GetLastTransformParameters();
```

In the case of the `itk::TranslationTransform`, there is a straightforward interpretation of the parameters. Each element of the array corresponds to a translation along one spatial dimension.

```
const double TranslationAlongX = finalParameters[0];
const double TranslationAlongY = finalParameters[1];
```

The optimizer can be queried for the actual number of iterations performed to reach convergence. The `GetCurrentIteration()` method returns this value. A large number of iterations may be an indication that the maximum step length has been set too small, which is undesirable since it results in long computational times.

```
const unsigned int numberOfIterations = optimizer->GetCurrentIteration();
```

The value of the image metric corresponding to the last set of parameters can be obtained with the `GetValue()` method of the optimizer.

```
const double bestValue = optimizer->GetValue();
```

Let's execute this example over two of the images provided in `Examples/Data`:

- `QB_Suburb.png`
- `QB_Suburb13x17y.png`

The second image is the result of intentionally translating the first image by $(13, 17)$ pixels. Both images have unit-spacing and are shown in Figure 9.3. The registration takes 18 iterations and the resulting transform parameters are:

```
Translation X = 12.0192
Translation Y = 16.0231
```

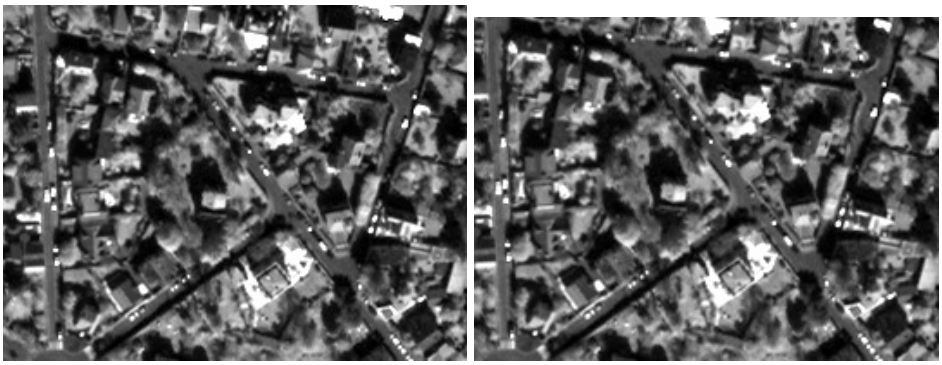


Figure 9.3: Fixed and Moving image provided as input to the registration method.

As expected, these values match quite well the misalignment that we intentionally introduced in the moving image.

It is common, as the last step of a registration task, to use the resulting transform to map the moving image into the fixed image space. This is easily done with the `itk::ResampleImageFilter`. First, a ResampleImageFilter type is instantiated using the image types. It is convenient to use the fixed image type as the output type since it is likely that the transformed moving image will be compared with the fixed image.

```
typedef itk::ResampleImageFilter<
    MovingImageType,
    FixedImageType>    ResampleFilterType;
```

A resampling filter is created and the moving image is connected as its input.

```
ResampleFilterType::Pointer resampler = ResampleFilterType::New();
resampler->SetInput(movingImageReader->GetOutput());
```

The Transform that is produced as output of the Registration method is also passed as input to the resampling filter. Note the use of the methods `GetOutput()` and `Get()`. This combination is needed here because the registration method acts as a filter whose output is a transform decorated in the form of a `itk::DataObject`. For details in this construction you may want to read the documentation of the `itk::DataObjectDecorator`.

```
resampler->SetTransform(registration->GetOutput()->Get());
```

The ResampleImageFilter requires additional parameters to be specified, in particular, the spacing, origin and size of the output image. The default pixel value is also set to a distinct gray level in order to highlight the regions that are mapped outside of the moving image.

```
FixedImageType::Pointer fixedImage = fixedImageReader->GetOutput();
resampler->SetSize(fixedImage->GetLargestPossibleRegion().GetSize());
```

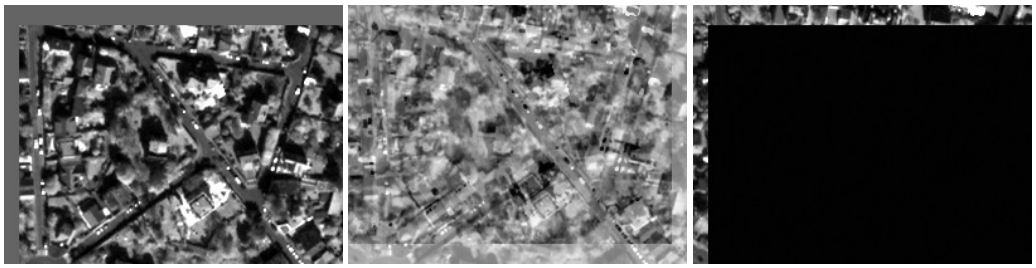


Figure 9.4: Mapped moving image and its difference with the fixed image before and after registration

```
resampler->SetOutputOrigin(fixedImage->GetOrigin());
resampler->SetOutputSpacing(fixedImage->GetSpacing());
resampler->SetDefaultPixelValue(100);
```

The output of the filter is passed to a writer that will store the image in a file. An `itk::CastImageFilter` is used to convert the pixel type of the resampled image to the final type used by the writer. The cast and writer filters are instantiated below.

```
typedef unsigned char                           OutputPixelType;
typedef otb::Image<OutputPixelType, Dimension> OutputImageType;
typedef itk::CastImageFilter<FixedImageType,
    OutputImageType>  CastFilterType;
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

The filters are created by invoking their `New()` method.

```
WriterType::Pointer     writer =  WriterType::New();
CastFilterType::Pointer caster =  CastFilterType::New();
```

The filters are connected together and the `Update()` method of the writer is invoked in order to trigger the execution of the pipeline.

```
caster->SetInput(resampler->GetOutput());
writer->SetInput(caster->GetOutput());
writer->Update();
```

The fixed image and the transformed moving image can easily be compared using the `itk::SubtractImageFilter`. This pixel-wise filter computes the difference between homologous pixels of its two input images.

```
typedef itk::SubtractImageFilter<
    FixedImageType,
    FixedImageType,
    FixedImageType> DifferenceFilterType;

DifferenceFilterType::Pointer difference = DifferenceFilterType::New();
```

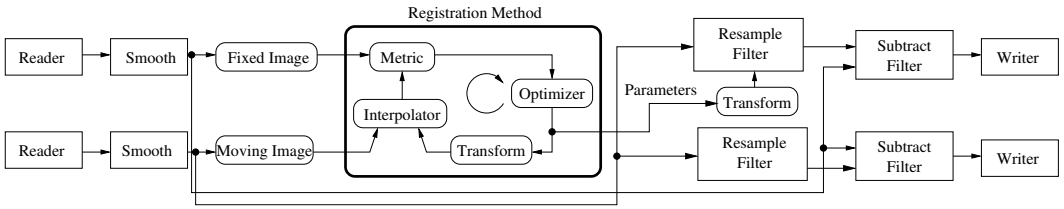


Figure 9.5: Pipeline structure of the registration example.

```
difference->SetInput1(fixedImageReader->GetOutput());
difference->SetInput2(resampler->GetOutput());
```

Note that the use of subtraction as a method for comparing the images is appropriate here because we chose to represent the images using a pixel type `float`. A different filter would have been used if the pixel type of the images were any of the `unsigned` integer type.

Since the differences between the two images may correspond to very low values of intensity, we rescale those intensities with a `itk::RescaleIntensityImageFilter` in order to make them more visible. This rescaling will also make possible to visualize the negative values even if we save the difference image in a file format that only support unsigned pixel values[1]. We also reduce the `DefaultPixelValue` to "1" in order to prevent that value from absorbing the dynamic range of the differences between the two images.

```
typedef itk::RescaleIntensityImageFilter<
    FixedImageType,
    OutputImageType>   RescalerType;

RescalerType::Pointer intensityRescaler = RescalerType::New();

intensityRescaler->SetInput(difference->GetOutput());
intensityRescaler->SetOutputMinimum(0);
intensityRescaler->SetOutputMaximum(255);

resampler->SetDefaultPixelValue(1);
```

Its output can be passed to another writer.

```
WriterType::Pointer writer2 = WriterType::New();
writer2->SetInput(intensityRescaler->GetOutput());
```

For the purpose of comparison, the difference between the fixed image and the moving image before registration can also be computed by simply setting the transform to an identity transform. Note that the resampling is still necessary because the moving image does not necessarily have the same spacing, origin and number of pixels as the fixed image. Therefore a pixel-by-pixel operation cannot

[1]This is the case of PNG, BMP, JPEG and TIFF among other common file formats.

in general be performed. The resampling process with an identity transform will ensure that we have a representation of the moving image in the grid of the fixed image.

```
TransformType::Pointer identityTransform = TransformType::New();
identityTransform->SetIdentity();
resampler->SetTransform(identityTransform);
```

The complete pipeline structure of the current example is presented in Figure 9.5. The components of the registration method are depicted as well. Figure 9.4 (left) shows the result of resampling the moving image in order to map it onto the fixed image space. The top and right borders of the image appear in the gray level selected with the `SetDefaultPixelValue()` in the ResampleImageFilter. The center image shows the difference between the fixed image and the original moving image. That is, the difference before the registration is performed. The right image shows the difference between the fixed image and the transformed moving image. That is, after the registration has been performed. Both difference images have been rescaled in intensity in order to highlight those pixels where differences exist. Note that the final registration is still off by a fraction of a pixel, which results in bands around edges of anatomical structures to appear in the difference image. A perfect registration would have produced a null difference image.

9.3 Features of the Registration Framework

This section presents a discussion on the two most common difficulties that users encounter when they start using the ITK registration framework. They are, in order of difficulty

- The direction of the Transform mapping
- The fact that registration is done in physical coordinates

Probably the reason why these two topics tend to create confusion is that they are implemented in different ways in other systems and therefore users tend to have different expectations regarding how things should work in OTB. The situation is further complicated by the fact that most people describe image operations as if they were manually performed in a picture in paper.

9.3.1 Direction of the Transform Mapping

The Transform that is optimized in the ITK registration framework is the one that maps points from the physical space of the fixed image into the physical space of the moving image. This is illustrated in Figure 9.6. This implies that the Transform will accept as input points from the fixed image and it will compute the coordinates of the analogous points in the moving image. What tends to create confusion is the fact that when the Transform shifts a point on the **positive** X direction, the visual effect of this mapping, once the moving image is resampled, is equivalent to *manually shifting* the

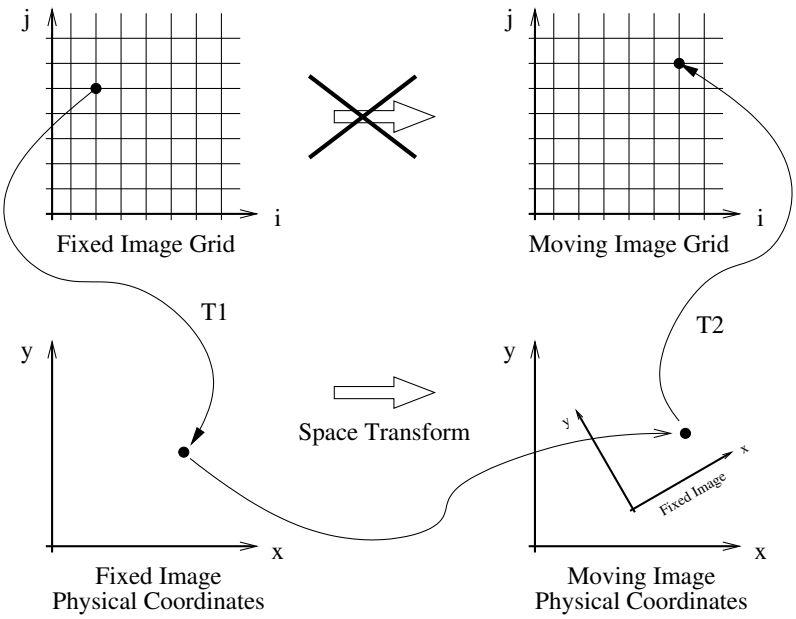


Figure 9.6: Different coordinate systems involved in the image registration process. Note that the transform being optimized is the one mapping from the physical space of the fixed image into the physical space of the moving image.

moving image along the **negative** X direction. In the same way, when the Transform applies a **clock-wise** rotation to the fixed image points, the visual effect of this mapping once the moving image has been resampled is equivalent to *manually rotating* the moving image **counter-clock-wise**.

The reason why this direction of mapping has been chosen for the ITK implementation of the registration framework is that this is the direction that better fits the fact that the moving image is expected to be resampled using the grid of the fixed image. The nature of the resampling process is such that an algorithm must go through every pixel of the *fixed* image and compute the intensity that should be assigned to this pixel from the mapping of the *moving* image. This computation involves taking the integral coordinates of the pixel in the image grid, usually called the "(i,j)" coordinates, mapping them into the physical space of the fixed image (transform **T1** in Figure 9.6), mapping those physical coordinates into the physical space of the moving image (Transform to be optimized), then mapping the physical coordinates of the moving image in to the integral coordinates of the discrete grid of the moving image (transform **T2** in the figure), where the value of the pixel intensity will be computed by interpolation.

If we have used the Transform that maps coordinates from the moving image physical space into the fixed image physical space, then the resampling process could not guarantee that every pixel in the grid of the fixed image was going to receive one and only one value. In other words, the resampling will have resulted in an image with holes and with redundant or overlapped pixel values.

As you have seen in the previous examples, and you will corroborate in the remaining examples in this chapter, the Transform computed by the registration framework is the Transform that can be used directly in the resampling filter in order to map the moving image into the discrete grid of the fixed image.

There are exceptional cases in which the transform that you want is actually the inverse transform of the one computed by the ITK registration framework. Only in those cases you may have to recur to invoking the `GetInverse()` method that most transforms offer. Make sure that before you consider following that dark path, you interact with the examples of resampling in order to get familiar with the correct interpretation of the transforms.

9.3.2 Registration is done in physical space

The second common difficulty that users encounter with the ITK registration framework is related to the fact that ITK performs registration in the context of physical space and not in the discrete space of the image grid. Figure 9.6 show this concept by crossing the transform that goes between the two image grids. One important consequence of this fact is that having the correct image origin and image pixel size is fundamental for the success of the registration process in ITK. Users must make sure that they provide correct values for the origin and spacing of both the fixed and moving images.

A typical case that helps to understand this issue, is to consider the registration of two images where one has a pixel size different from the other. For example, a SPOt 5 image and a QuickBird image. Typically a Quickbird image will have a pixel size in the order of 0.6 m, while a SPOT 5 image will

have a pixel size of 2.5 m.

A user performing registration between a SPOT 5 image and a Quickbird image may be naively expecting that because the SPOT 5 image has less pixels, a *scaling* factor is required in the Transform in order to map this image into the Quickbird image. At that point, this person is attempting to interpret the registration process directly between the two image grids, or in *pixel space*. What ITK will do in this case is to take into account the pixel size that the user has provided and it will use that pixel size in order to compute a scaling factor for Transforms *T1* and *T2* in Figure 9.6. Since these two transforms take care of the required scaling factor, the spatial Transform to be computed during the registration process does not need to be concerned about such scaling. The transform that ITK is computing is the one that will physically map the landscape the moving image into the landscape of the fixed image.

In order to better understand this concepts, it is very useful to draw sketches of the fixed and moving image *at scale* in the same physical coordinate system. That is the geometrical configuration that the ITK registration framework uses as context. Keeping this in mind helps a lot for interpreting correctly the results of a registration process performed with ITK.

9.4 Multi-Modality Registration

Some of the most challenging cases of image registration arise when images of different modalities are involved. In such cases, metrics based on direct comparison of gray levels are not applicable. It has been extensively shown that metrics based on the evaluation of mutual information are well suited for overcoming the difficulties of multi-modality registration.

The concept of Mutual Information is derived from Information Theory and its application to image registration has been proposed in different forms by different groups [28, 90, 134], a more detailed review can be found in [69]. The OTB, through ITK, currently provides five different implementations of Mutual Information metrics (see section 9.7 for details). The following example illustrates the practical use of some of these metrics.

9.4.1 Viola-Wells Mutual Information

The source code for this example can be found in the file
`Examples/Registration/ImageRegistration2.cxx`.

The following simple example illustrates how multiple imaging modalities can be registered using the ITK registration framework. The first difference between this and previous examples is the use of the `itk::MutualInformationImageToImageMetric` as the cost-function to be optimized. The second difference is the use of the `itk::GradientDescentOptimizer`. Due to the stochastic nature of the metric computation, the values are too noisy to work successfully with the `itk::RegularStepGradientDescentOptimizer`. Therefore, we will use the simpler GradientDescentOptimizer with a user defined learning rate. The following headers declare the basic

components of this registration method.

```
#include "itkImageRegistrationMethod.h"
#include "itkTranslationTransform.h"
#include "itkMutualInformationImageToImageMetric.h"
#include "itkLinearInterpolateImageFunction.h"
#include "itkGradientDescentOptimizer.h"
#include "otbImage.h"
```

One way to simplify the computation of the mutual information is to normalize the statistical distribution of the two input images. The `itk::NormalizeImageFilter` is the perfect tool for this task. It rescales the intensities of the input images in order to produce an output image with zero mean and unit variance.

```
#include "itkNormalizeImageFilter.h"
```

Additionally, low-pass filtering of the images to be registered will also increase robustness against noise. In this example, we will use the `itk::DiscreteGaussianImageFilter` for that purpose. The characteristics of this filter have been discussed in Section 8.7.1.

```
#include "itkDiscreteGaussianImageFilter.h"
```

The moving and fixed images types should be instantiated first.

```
  const unsigned int Dimension = 2;
  typedef  unsigned short PixelType;

  typedef otb::Image<PixelType, Dimension> FixedImageType;
  typedef otb::Image<PixelType, Dimension> MovingImageType;
```

It is convenient to work with an internal image type because mutual information will perform better on images with a normalized statistical distribution. The fixed and moving images will be normalized and converted to this internal type.

```
  typedef float                                    InternalPixelType;
  typedef otb::Image<InternalPixelType, Dimension> InternalImageType;
```

The rest of the image registration components are instantiated as illustrated in Section 9.2 with the use of the `InternalImageType`.

```
  typedef itk::TranslationTransform<double, Dimension> TransformType;
  typedef itk::GradientDescentOptimizer                OptimizerType;

  typedef itk::LinearInterpolateImageFunction<InternalImageType,
      double> InterpolatorType;

  typedef itk::ImageRegistrationMethod<InternalImageType,
      InternalImageType>  RegistrationType;
```

The mutual information metric type is instantiated using the image types.

```
typedef itk::MutualInformationImageToImageMetric<
    InternalImageType,
    InternalImageType >    MetricType;
```

The metric is created using the `New()` method and then connected to the registration object.

```
MetricType::Pointer metric        = MetricType::New();
registration->SetMetric(metric);
```

The metric requires a number of parameters to be selected, including the standard deviation of the Gaussian kernel for the fixed image density estimate, the standard deviation of the kernel for the moving image density and the number of samples use to compute the densities and entropy values. Details on the concepts behind the computation of the metric can be found in Section 9.7.4. Experience has shown that a kernel standard deviation of 0.4 works well for images which have been normalized to a mean of zero and unit variance. We will follow this empirical rule in this example.

```
metric->SetFixedImageStandardDeviation(0.4);
metric->SetMovingImageStandardDeviation(0.4);
```

The normalization filters are instantiated using the fixed and moving image types as input and the internal image type as output.

```
typedef itk::NormalizeImageFilter<
    FixedImageType,
    InternalImageType
    > FixedNormalizeFilterType;

typedef itk::NormalizeImageFilter<
    MovingImageType,
    InternalImageType
    > MovingNormalizeFilterType;

FixedNormalizeFilterType::Pointer fixedNormalizer =
  FixedNormalizeFilterType::New();

MovingNormalizeFilterType::Pointer movingNormalizer =
  MovingNormalizeFilterType::New();
```

The blurring filters are declared using the internal image type as both the input and output types. In this example, we will set the variance for both blurring filters to 2.0.

```
typedef itk::DiscreteGaussianImageFilter<
    InternalImageType,
    InternalImageType
    > GaussianFilterType;

GaussianFilterType::Pointer fixedSmoother  = GaussianFilterType::New();
GaussianFilterType::Pointer movingSmoother = GaussianFilterType::New();

fixedSmoother->SetVariance(4.0);
movingSmoother->SetVariance(4.0);
```

The output of the readers becomes the input to the normalization filters. The output of the normalization filters is connected as input to the blurring filters. The input to the registration method is taken from the blurring filters.

```
fixedNormalizer->SetInput(fixedImageReader->GetOutput());
movingNormalizer->SetInput(movingImageReader->GetOutput());

fixedSmoother->SetInput(fixedNormalizer->GetOutput());
movingSmoother->SetInput(movingNormalizer->GetOutput());

registration->SetFixedImage(fixedSmoother->GetOutput());
registration->SetMovingImage(movingSmoother->GetOutput());
```

We should now define the number of spatial samples to be considered in the metric computation. Note that we were forced to postpone this setting until we had done the preprocessing of the images because the number of samples is usually defined as a fraction of the total number of pixels in the fixed image.

The number of spatial samples can usually be as low as 1% of the total number of pixels in the fixed image. Increasing the number of samples improves the smoothness of the metric from one iteration to another and therefore helps when this metric is used in conjunction with optimizers that rely of the continuity of the metric values. The trade-off, of course, is that a larger number of samples result in longer computation times per every evaluation of the metric.

It has been demonstrated empirically that the number of samples is not a critical parameter for the registration process. When you start fine tuning your own registration process, you should start using high values of number of samples, for example in the range of 20% to 50% of the number of pixels in the fixed image. Once you have succeeded to register your images you can then reduce the number of samples progressively until you find a good compromise on the time it takes to compute one evaluation of the Metric. Note that it is not useful to have very fast evaluations of the Metric if the noise in their values results in more iterations being required by the optimizer to converge.

```
const unsigned int numberOfPixels = fixedImageRegion.GetNumberOfPixels();

const unsigned int numberOfSamples =
  static_cast<unsigned int>(numberOfPixels * 0.01);

metric->SetNumberOfSpatialSamples(numberOfSamples);
```

Since larger values of mutual information indicate better matches than smaller values, we need to maximize the cost function in this example. By default the GradientDescentOptimizer class is set to minimize the value of the cost-function. It is therefore necessary to modify its default behavior by invoking the `MaximizeOn()` method. Additionally, we need to define the optimizer's step size using the `SetLearningRate()` method.

```
optimizer->SetLearningRate(150.0);
optimizer->SetNumberOfIterations(300);
optimizer->MaximizeOn();
```

Figure 9.7: A SAR image (fixed image) and an aerial photograph (moving image) are provided as input to the registration method.

Note that large values of the learning rate will make the optimizer unstable. Small values, on the other hand, may result in the optimizer needing too many iterations in order to walk to the extrema of the cost function. The easy way of fine tuning this parameter is to start with small values, probably in the range of $\{5.0, 10.0\}$. Once the other registration parameters have been tuned for producing convergence, you may want to revisit the learning rate and start increasing its value until you observe that the optimization becomes unstable. The ideal value for this parameter is the one that results in a minimum number of iterations while still keeping a stable path on the parametric space of the optimization. Keep in mind that this parameter is a multiplicative factor applied on the gradient of the Metric. Therefore, its effect on the optimizer step length is proportional to the Metric values themselves. Metrics with large values will require you to use smaller values for the learning rate in order to maintain a similar optimizer behavior.

Let's execute this example over two of the images provided in `Examples/Data`:

- `RamsesROISmall.png`
- `ADS40RoiSmall.png`

The moving image after resampling is presented on the left side of Figure 9.8. The center and right figures present a checkerboard composite of the fixed and moving images before and after registration. Since the real deformation between the 2 images is not simply a shift, some registration errors remain, but the left part of the images is correctly registered.

Figure 9.8: Mapped moving image (left) and composition of fixed and moving images before (center) and after (right) registration.

9.5 Centered Transforms

The OTB/ITK image coordinate origin is typically located in one of the image corners (see section 5.1.4 for details). This results in counter-intuitive transform behavior when rotations and scaling are involved. Users tend to assume that rotations and scaling are performed around a fixed point at the center of the image. In order to compensate for this difference in natural interpretation, the concept of *centered* transforms have been introduced into the toolkit. The following sections describe the main characteristics of such transforms.

9.5.1 Rigid Registration in 2D

The source code for this example can be found in the file
`Examples/Registration/ImageRegistration5.cxx`.

This example illustrates the use of the `itk::CenteredRigid2DTransform` for performing rigid registration in $2D$. The example code is for the most part identical to that presented in Section 9.2. The main difference is the use of the CenteredRigid2DTransform here instead of the `itk::TranslationTransform`.

In addition to the headers included in previous examples, the following header must also be included.

```
#include "itkCenteredRigid2DTransform.h"
```

The transform type is instantiated using the code below. The only template parameter for this class is the representation type of the space coordinates.

```
  typedef itk::CenteredRigid2DTransform<double> TransformType;
```

The transform object is constructed below and passed to the registration method.

```
TransformType::Pointer transform = TransformType::New();
registration->SetTransform(transform);
```

Since we are working with high resolution images and expected shifts are larger than the resolution, we will need to smooth the images in order to avoid the optimizer to get stucked on local minima. In order to do this, we will use a simple mean filter.

```
typedef itk::MeanImageFilter<
    FixedImageType, FixedImageType>  FixedFilterType;

typedef itk::MeanImageFilter<
    MovingImageType, MovingImageType>  MovingFilterType;

FixedFilterType::Pointer  fixedFilter  = FixedFilterType::New();
MovingFilterType::Pointer movingFilter = MovingFilterType::New();

FixedImageType::SizeType indexFRadius;

indexFRadius[0] = 4; // radius along x
indexFRadius[1] = 4; // radius along y

fixedFilter->SetRadius(indexFRadius);

MovingImageType::SizeType indexMRadius;

indexMRadius[0] = 4; // radius along x
indexMRadius[1] = 4; // radius along y

movingFilter->SetRadius(indexMRadius);

fixedFilter->SetInput(fixedImageReader->GetOutput());
movingFilter->SetInput(movingImageReader->GetOutput());
```

Now we can plug the output of the smoothing filters at the input of the registration method.

```
registration->SetFixedImage(fixedFilter->GetOutput());
registration->SetMovingImage(movingFilter->GetOutput());
```

In this example, the input images are taken from readers. The code below updates the readers in order to ensure that the image parameters (size, origin and spacing) are valid when used to initialize the transform. We intend to use the center of the fixed image as the rotation center and then use the vector between the fixed image center and the moving image center as the initial translation to be applied after the rotation.

```
fixedImageReader->Update();
movingImageReader->Update();
```

The center of rotation is computed using the origin, size and spacing of the fixed image.

```
FixedImageType::Pointer fixedImage = fixedImageReader->GetOutput();
```

```
const SpacingType fixedSpacing = fixedImage->GetSpacing();
const OriginType  fixedOrigin  = fixedImage->GetOrigin();
const RegionType  fixedRegion  = fixedImage->GetLargestPossibleRegion();
const SizeType    fixedSize    = fixedRegion.GetSize();

TransformType::InputPointType centerFixed;

centerFixed[0] = fixedOrigin[0] + fixedSpacing[0] * fixedSize[0] / 2.0;
centerFixed[1] = fixedOrigin[1] + fixedSpacing[1] * fixedSize[1] / 2.0;
```

The center of the moving image is computed in a similar way.

```
MovingImageType::Pointer movingImage = movingImageReader->GetOutput();

const SpacingType movingSpacing = movingImage->GetSpacing();
const OriginType  movingOrigin  = movingImage->GetOrigin();
const RegionType  movingRegion  = movingImage->GetLargestPossibleRegion();
const SizeType    movingSize    = movingRegion.GetSize();

TransformType::InputPointType centerMoving;

centerMoving[0] = movingOrigin[0] + movingSpacing[0] * movingSize[0] / 2.0;
centerMoving[1] = movingOrigin[1] + movingSpacing[1] * movingSize[1] / 2.0;
```

The most straightforward method of initializing the transform parameters is to configure the transform and then get its parameters with the method `GetParameters()`. Here we initialize the transform by passing the center of the fixed image as the rotation center with the `SetCenter()` method. Then the translation is set as the vector relating the center of the moving image to the center of the fixed image. This last vector is passed with the method `SetTranslation()`.

```
transform->SetCenter(centerFixed);
transform->SetTranslation(centerMoving - centerFixed);
```

Let's finally initialize the rotation with a zero angle.

```
transform->SetAngle(0.0);
```

Now we pass the current transform's parameters as the initial parameters to be used when the registration process starts.

```
registration->SetInitialTransformParameters(transform->GetParameters());
```

Keeping in mind that the scale of units in rotation and translation is quite different, we take advantage of the scaling functionality provided by the optimizers. We know that the first element of the parameters array corresponds to the angle that is measured in radians, while the other parameters correspond to translations that are measured in the units of the spacin (pixels in our case). For this reason we use small factors in the scales associated with translations and the coordinates of the rotation center .

```
typedef OptimizerType::ScalesType OptimizerScalesType;
OptimizerScalesType optimizerScales(transform->GetNumberOfParameters());
const double        translationScale = 1.0 / 1000.0;

optimizerScales[0] = 1.0;
optimizerScales[1] = translationScale;
optimizerScales[2] = translationScale;
optimizerScales[3] = translationScale;
optimizerScales[4] = translationScale;

optimizer->SetScales(optimizerScales);
```

Next we set the normal parameters of the optimization method. In this case we are using an `itk::RegularStepGradientDescentOptimizer`. Below, we define the optimization parameters like the relaxation factor, initial step length, minimal step length and number of iterations. These last two act as stopping criteria for the optimization.

```
double initialStepLength = 0.1;
```

```
optimizer->SetRelaxationFactor(0.6);
optimizer->SetMaximumStepLength(initialStepLength);
optimizer->SetMinimumStepLength(0.001);
optimizer->SetNumberOfIterations(200);
```

Let's execute this example over two of the images provided in `Examples/Data`:

- `QB_Suburb.png`
- `QB_SuburbRotated10.png`

The second image is the result of intentionally rotating the first image by 10 degrees around the geometrical center of the image. Both images have unit-spacing and are shown in Figure 9.9. The registration takes 21 iterations and produces the results:

```
[0.176168, 134.515, 103.011, -0.00182313, 0.0717891]
```

These results are interpreted as

- Angle = 0.176168 radians
- Center = $(134.515, 103.011)$ pixels
- Translation = $(-0.00182313, 0.0717891)$ pixels

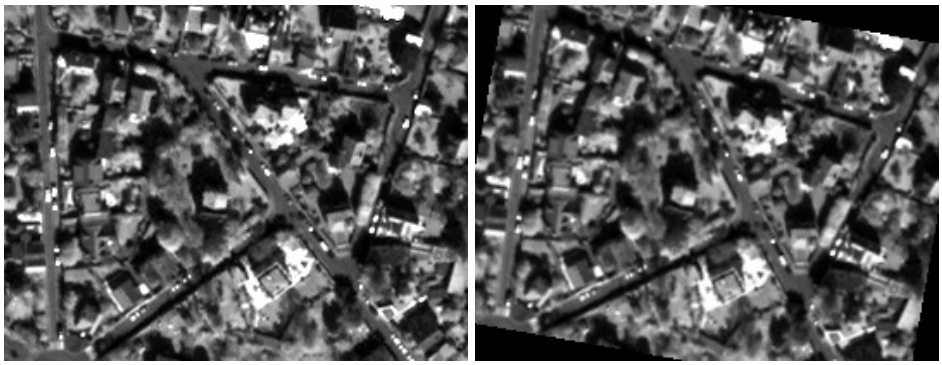


Figure 9.9: Fixed and moving images are provided as input to the registration method using the Centered-Rigid2D transform.

Figure 9.10: Resampled moving image (left). Differences between the fixed and moving images, before (center) and after (right) registration using the CenteredRigid2D transform.

As expected, these values match the misalignment intentionally introduced into the moving image quite well, since 10 degrees is about 0.174532 radians.

Figure 9.10 shows from left to right the resampled moving image after registration, the difference between fixed and moving images before registration, and the difference between fixed and resampled moving image after registration. It can be seen from the last difference image that the rotational component has been solved but that a small centering misalignment persists.

Let's now consider the case in which rotations and translations are present in the initial registration, as in the following pair of images:

- `QB_Suburb.png`
- `QB_SuburbR10X13Y17.png`

The second image is the result of intentionally rotating the first image by 10 degrees and then translating it 13 pixels in X and 17 pixels in Y. Both images have unit-spacing and are shown in Figure 9.11. In order to accelerate convergence it is convenient to use a larger step length as shown here.

```
optimizer->SetMaximumStepLength( 1.0 );
```

The registration now takes 34 iterations and produces the following results:

```
[0.176125, 135.553, 102.159, -11.9102, -15.8045]
```

These parameters are interpreted as

- Angle = 0.176125 radians
- Center = $(135.553, 102.159)$ millimeters
- Translation = $(-11.9102, -15.8045)$ millimeters

These values approximately match the initial misalignment intentionally introduced into the moving image, since 10 degrees is about 0.174532 radians. The horizontal translation is well resolved while the vertical translation ends up being off by about one millimeter.

Figure 9.12 shows the output of the registration. The rightmost image of this figure shows the difference between the fixed image and the resampled moving image after registration.

9.5.2 Centered Affine Transform

The source code for this example can be found in the file `Examples/Registration/ImageRegistration9.cxx`.

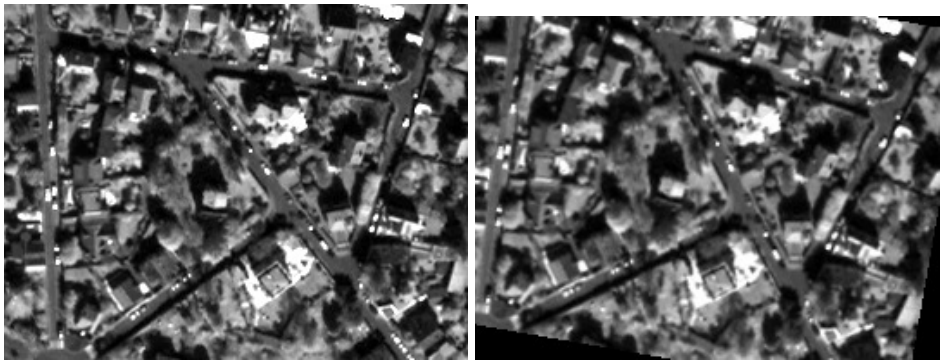


Figure 9.11: Fixed and moving images provided as input to the registration method using the CenteredRigid2D transform.

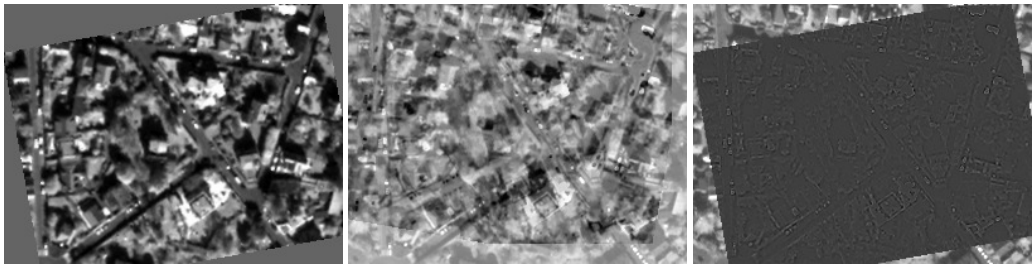


Figure 9.12: Resampled moving image (left). Differences between the fixed and moving images, before (center) and after (right) registration with the CenteredRigid2D transform.

This example illustrates the use of the `itk::AffineTransform` for performing registration. The example code is, for the most part, identical to previous ones. The main difference is the use of the AffineTransform here instead of the `itk::CenteredRigid2DTransform`. We will focus on the most relevant changes in the current code and skip the basic elements already explained in previous examples.

Let's start by including the header file of the AffineTransform.

```
#include "itkAffineTransform.h"
```

We define then the types of the images to be registered.

```
const unsigned int Dimension = 2;
typedef  float PixelType;

typedef otb::Image<PixelType, Dimension> FixedImageType;
typedef otb::Image<PixelType, Dimension> MovingImageType;
```

The transform type is instantiated using the code below. The template parameters of this class are the representation type of the space coordinates and the space dimension.

```
typedef itk::AffineTransform<
    double,
    Dimension>     TransformType;
```

The transform object is constructed below and passed to the registration method.

```
TransformType::Pointer transform = TransformType::New();
registration->SetTransform(transform);
```

Since we are working with high resolution images and expected shifts are larger than the resolution, we will need to smooth the images in order to avoid the optimizer to get stucked on local minima. In order to do this, we will use a simple mean filter.

```
typedef itk::MeanImageFilter<
    FixedImageType, FixedImageType>  FixedFilterType;

typedef itk::MeanImageFilter<
    MovingImageType, MovingImageType>  MovingFilterType;

FixedFilterType::Pointer  fixedFilter  = FixedFilterType::New();
MovingFilterType::Pointer movingFilter = MovingFilterType::New();

FixedImageType::SizeType indexFRadius;

indexFRadius[0] = 4; // radius along x
indexFRadius[1] = 4; // radius along y

fixedFilter->SetRadius(indexFRadius);

MovingImageType::SizeType indexMRadius;
```

```
indexMRadius[0] = 4; // radius along x
indexMRadius[1] = 4; // radius along y

movingFilter->SetRadius(indexMRadius);

fixedFilter->SetInput(fixedImageReader->GetOutput());
movingFilter->SetInput(movingImageReader->GetOutput());
```

Now we can plug the output of the smoothing filters at the input of the registration method.

```
registration->SetFixedImage(fixedFilter->GetOutput());
registration->SetMovingImage(movingFilter->GetOutput());
```

In this example, we use the `itk::CenteredTransformInitializer` helper class in order to compute a reasonable value for the initial center of rotation and the translation. The initializer is set to use the center of mass of each image as the initial correspondence correction.

```
typedef itk::CenteredTransformInitializer<
    TransformType,
    FixedImageType,
    MovingImageType>  TransformInitializerType;
TransformInitializerType::Pointer initializer = TransformInitializerType::New();
initializer->SetTransform(transform);
initializer->SetFixedImage(fixedImageReader->GetOutput());
initializer->SetMovingImage(movingImageReader->GetOutput());
initializer->MomentsOn();
initializer->InitializeTransform();
```

Now we pass the parameters of the current transform as the initial parameters to be used when the registration process starts.

```
registration->SetInitialTransformParameters(
  transform->GetParameters());
```

Keeping in mind that the scale of units in scaling, rotation and translation are quite different, we take advantage of the scaling functionality provided by the optimizers. We know that the first $N \times N$ elements of the parameters array correspond to the rotation matrix factor, the next N correspond to the rotation center, and the last N are the components of the translation to be applied after multiplication with the matrix is performed.

```
typedef OptimizerType::ScalesType OptimizerScalesType;
OptimizerScalesType optimizerScales(transform->GetNumberOfParameters());

optimizerScales[0] =  1.0;
optimizerScales[1] =  1.0;
optimizerScales[2] =  1.0;
optimizerScales[3] =  1.0;
optimizerScales[4] =  translationScale;
optimizerScales[5] =  translationScale;

optimizer->SetScales(optimizerScales);
```

We also set the usual parameters of the optimization method. In this case we are using an `itk::RegularStepGradientDescentOptimizer`. Below, we define the optimization parameters like initial step length, minimal step length and number of iterations. These last two act as stopping criteria for the optimization.

```
optimizer->SetMaximumStepLength(steplength);
optimizer->SetMinimumStepLength(0.0001);
optimizer->SetNumberOfIterations(maxNumberOfIterations);
```

We also set the optimizer to do minimization by calling the `MinimizeOn()` method.

```
optimizer->MinimizeOn();
```

Finally we trigger the execution of the registration method by calling the `Update()` method. The call is placed in a `try/catch` block in case any exceptions are thrown.

```
try
  {
  registration->Update();
  }
catch (itk::ExceptionObject& err)
  {
  std::cerr << "ExceptionObject caught !" << std::endl;
  std::cerr << err << std::endl;
  return -1;
  }
```

Once the optimization converges, we recover the parameters from the registration method. This is done with the `GetLastTransformParameters()` method. We can also recover the final value of the metric with the `GetValue()` method and the final number of iterations with the `GetCurrentIteration()` method.

```
OptimizerType::ParametersType finalParameters =
  registration->GetLastTransformParameters();

const double finalRotationCenterX = transform->GetCenter()[0];
const double finalRotationCenterY = transform->GetCenter()[1];
const double finalTranslationX    = finalParameters[4];
const double finalTranslationY    = finalParameters[5];

const unsigned int numberOfIterations = optimizer->GetCurrentIteration();
const double       bestValue = optimizer->GetValue();
```

Let's execute this example over two of the images provided in `Examples/Data`:

- `QB_Suburb.png`
- `QB_SuburbR10X13Y17.png`

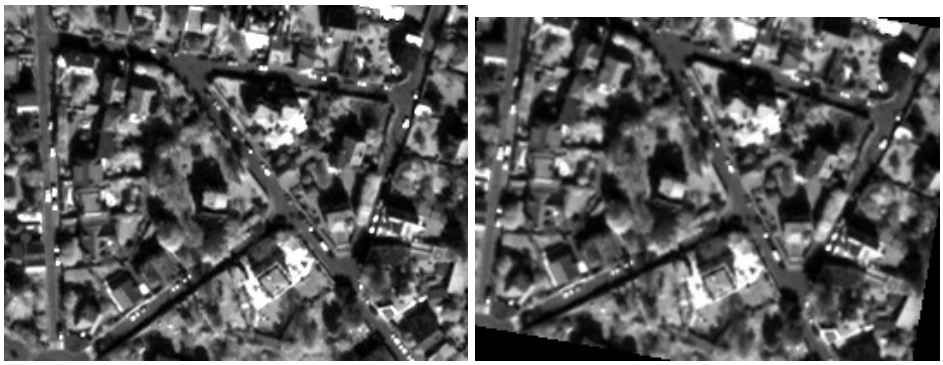


Figure 9.13: Fixed and moving images provided as input to the registration method using the AffineTransform.

The second image is the result of intentionally rotating the first image by 10 degrees and then translating by $(13, 17)$. Both images have unit-spacing and are shown in Figure 9.13. We execute the code using the following parameters: step length=1.0, translation scale= 0.0001 and maximum number of iterations = 300. With these images and parameters the registration takes 83 iterations and produces

```
20.2134   [0.983291, -0.173507, 0.174626, 0.983028, -12.1899, -16.0882]
```

These results are interpreted as

- Iterations = 83
- Final Metric = 20.2134
- Center = $(134.152, 104.067)$ pixels
- Translation = $(-12.1899, -16.0882)$ pixels
- Affine scales = $(0.999024, 0.997875)$

The second component of the matrix values is usually associated with $\sin\theta$. We obtain the rotation through SVD of the affine matrix. The value is 10.0401 degrees, which is approximately the intentional misalignment of 10.0 degrees.

Figure 9.14 shows the output of the registration. The right most image of this figure shows the squared magnitude difference between the fixed image and the resampled moving image.

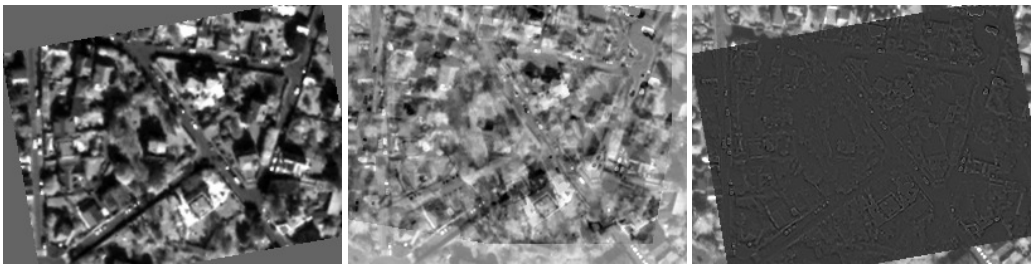


Figure 9.14: The resampled moving image (left), and the difference between the fixed and moving images before (center) and after (right) registration with the AffineTransform transform.

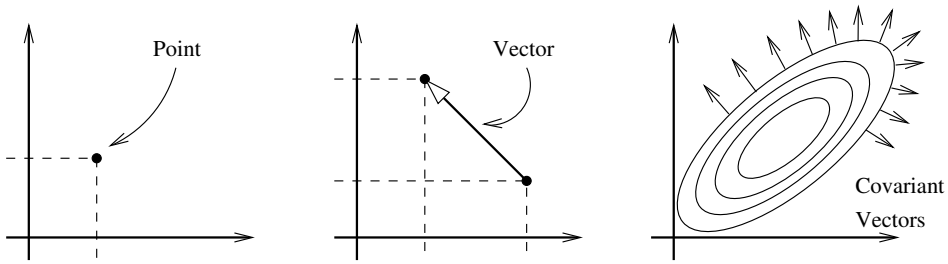


Figure 9.15: Geometric representation objects in ITK.

9.6 Transforms

In OTB, we use the Insight Toolkit `itk::Transform` objects encapsulate the mapping of points and vectors from an input space to an output space. If a transform is invertible, back transform methods are also provided. Currently, ITK provides a variety of transforms from simple translation, rotation and scaling to general affine and kernel transforms. Note that, while in this section we discuss transforms in the context of registration, transforms are general and can be used for other applications. Some of the most commonly used transforms will be discussed in detail later. Let's begin by introducing the objects used in ITK for representing basic spatial concepts.

9.6.1 Geometrical Representation

ITK implements a consistent geometric representation of the space. The characteristics of classes involved in this representation are summarized in Table 9.1. In this regard, ITK takes full advantage of the capabilities of Object Oriented programming and resists the temptation of using simple arrays of `float` or `double` in order to represent geometrical objects. The use of basic arrays would have blurred the important distinction between the different geometrical concepts and would have allowed for the innumerable conceptual and programming errors that result from using a vector where a point

Class	Geometrical concept
`itk::Point`	Position in space. In N-dimensional space it is represented by an array of N numbers associated with space coordinates.
`itk::Vector`	Relative position between two points. In N-dimensional space it is represented by an array of N numbers, each one associated with the distance along a coordinate axis. Vectors do not have a position in space. A vector is defined as the subtraction of two points.
`itk::CovariantVector`	Orthogonal direction to a $(N-1)$-dimensional manifold in space. For example, in $3D$ it corresponds to the vector orthogonal to a surface. This is the appropriate class for representing Gradients of functions. Covariant vectors do not have a position in space. Covariant vector should not be added to Points, nor to Vectors.

Table 9.1: Summary of objects representing geometrical concepts in ITK.

is needed or vice versa.

Additional uses of the `itk::Point`, `itk::Vector` and `itk::CovariantVector` classes have been discussed in Chapter 5. Each one of these classes behaves differently under spatial transformations. It is therefore quite important to keep their distinction clear. Figure 9.15 illustrates the differences between these concepts.

Transform classes provide different methods for mapping each one of the basic space-representation objects. Points, vectors and covariant vectors are transformed using the methods `TransformPoint()`, `TransformVector()` and `TransformCovariantVector()` respectively.

One of the classes that deserve further comments is the `itk::Vector`. This ITK class tend to be misinterpreted as a container of elements instead of a geometrical object. This is a common misconception originated by the fact that Computer Scientist and Software Engineers misuse the term "Vector". The actual word "Vector" is relatively young. It was coined by William Hamilton in his book "*Elements of Quaternions*" published in 1886 (post-mortem)[55]. In the same text Hamilton coined the terms: "*Scalar*", "*Versor*" and "*Tensor*". Although the modern term of "*Tensor*" is used in Calculus in a different sense of what Hamilton defined in his book at the time [40].

A "*Vector*" is, by definition, a mathematical object that embodies the concept of "direction in space". Strictly speaking, a Vector describes the relationship between two Points in space, and captures both their relative distance and orientation.

Computer scientists and software engineers misused the term vector in order to represent the concept of an "Indexed Set" [7]. Mechanical Engineers and Civil Engineers, who deal with the real world of physical objects will not commit this mistake and will keep the word "*Vector*" attached to a geometrical concept. Biologists, on the other hand, will associate "*Vector*" to a "vehicle" that allows

them to direct something in a particular direction, for example, a virus that allows them to insert pieces of code into a DNA strand [88].

Textbooks in programming do not help to clarify those concepts and loosely use the term "*Vector*" for the purpose of representing an "enumerated set of common elements". STL follows this trend and continue using the word "*Vector*" for what it was not supposed to be used [7, 2]. Linear algebra separates the "*Vector*" from its notion of geometric reality and makes it an abstract set of numbers with arithmetic operations associated.

For those of you who are looking for the "*Vector*" in the Software Engineering sense, please look at the `itk::Array` and `itk::FixedArray` classes that actually provide such functionalities. Additionally, the `itk::VectorContainer` and `itk::MapContainer` classes may be of interest too. These container classes are intended for algorithms that require to insert and delete elements, and that may have large numbers of elements.

The Insight Toolkit deals with real objects that inhabit the physical space. This is particularly true in the context of the image registration framework. We chose to give the appropriate name to the mathematical objects that describe geometrical relationships in N-Dimensional space. It is for this reason that we explicitly make clear the distinction between Point, Vector and CovariantVector, despite the fact that most people would be happy with a simple use of `double[3]` for the three concepts and then will proceed to perform all sort of conceptually flawed operations such as

- Adding two Points
- Dividing a Point by a Scalar
- Adding a Covariant Vector to a Point
- Adding a Covariant Vector to a Vector

In order to enforce the correct use of the Geometrical concepts in ITK we organized these classes in a hierarchy that supports reuse of code and yet compartmentalize the behavior of the individual classes. The use of the `itk::FixedArray` as base class of the `itk::Point`, the `itk::Vector` and the `itk::CovariantVector` was a design decision based on calling things by their correct name.

An `itk::FixedArray` is an enumerated collection with a fixed number of elements. You can instantiate a fixed array of letters, or a fixed array of images, or a fixed array of transforms, or a fixed array of geometrical shapes. Therefore, the FixedArray only implements the functionality that is necessary to access those enumerated elements. No assumptions can be made at this point on any other operations required by the elements of the FixedArray, except the fact of having a default constructor.

The `itk::Point` is a type that represents the spatial coordinates of a spatial location. Based on geometrical concepts we defined the valid operations of the Point class. In particular we made sure that no `operator+()` was defined between Points, and that no `operator*( scalar )` nor `operator/( scalar )` were defined for Points.

In other words, you could do in ITK operations such as:

- Vector = Point - Point
- Point += Vector
- Point -= Vector
- Point = BarycentricCombination(Point, Point)

and you cannot (because you **should not**) do operation such as

- Point = Point * Scalar
- Point = Point + Point
- Point = Point / Scalar

The `itk::Vector` is, by Hamilton's definition, the subtraction between two points. Therefore a Vector must satisfy the following basic operations:

- Vector = Point - Point
- Point = Point + Vector
- Point = Point - Vector
- Vector = Vector + Vector
- Vector = Vector - Vector

An `itk::Vector` object is intended to be instantiated over elements that support mathematical operation such as addition, subtraction and multiplication by scalars.

9.6.2 Transform General Properties

Each transform class typically has several methods for setting its parameters. For example, `itk::Euler2DTransform` provides methods for specifying the offset, angle, and the entire rotation matrix. However, for use in the registration framework, the parameters are represented by a flat Array of doubles to facilitate communication with generic optimizers. In the case of the Euler2DTransform, the transform is also defined by three doubles: the first representing the angle, and the last two the offset. The flat array of parameters is defined using `SetParameters()`. A description of the parameters and their ordering is documented in the sections that follow.

In the context of registration, the transform parameters define the search space for optimizers. That is, the goal of the optimization is to find the set of parameters defining a transform that results in the best possible value of an image metric. The more parameters a transform has, the longer its

Behavior	Number of Parameters	Parameter Ordering	Restrictions
Maps every point to itself, every vector to itself and every covariant vector to itself.	0	NA	Only defined when the input and output space has the same number of dimensions.

Table 9.2: Characteristics of the identity transform.

computational time will be when used in a registration method since the dimension of the search space will be equal to the number of transform parameters.

Another requirement that the registration framework imposes on the transform classes is the computation of their Jacobians. In general, metrics require the knowledge of the Jacobian in order to compute Metric derivatives. The Jacobian is a matrix whose element are the partial derivatives of the output point with respect to the array of parameters that defines the transform:[2]

$$J = \begin{bmatrix} \frac{\partial x_1}{\partial p_1} & \frac{\partial x_1}{\partial p_2} & \cdots & \frac{\partial x_1}{\partial p_m} \\ \frac{\partial x_2}{\partial p_1} & \frac{\partial x_2}{\partial p_2} & \cdots & \frac{\partial x_2}{\partial p_m} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial x_n}{\partial p_1} & \frac{\partial x_n}{\partial p_2} & \cdots & \frac{\partial x_n}{\partial p_m} \end{bmatrix} \tag{9.1}$$

where $\{p_i\}$ are the transform parameters and $\{x_i\}$ are the coordinates of the output point. Within this framework, the Jacobian is represented by an `itk::Array2D` of doubles and is obtained from the transform by method `GetJacobian()`. The Jacobian can be interpreted as a matrix that indicates for a point in the input space how much its mapping on the output space will change as a response to a small variation in one of the transform parameters. Note that the values of the Jacobian matrix depend on the point in the input space. So actually the Jacobian can be noted as $J(\mathbf{X})$, where $\mathbf{X} = \{x_i\}$. The use of transform Jacobians enables the efficient computation of metric derivatives. When Jacobians are not available, metrics derivatives have to be computed using finite difference at a price of $2M$ evaluations of the metric value, where M is the number of transform parameters.

The following sections describe the main characteristics of the transform classes available in ITK.

9.6.3 Identity Transform

The identity transform `itk::IdentityTransform` is mainly used for debugging purposes. It is provided to methods that require a transform and in cases where we want to have the certainty

[2]Note that the term *Jacobian* is also commonly used for the matrix representing the derivatives of output point coordinates with respect to input point coordinates. Sometimes the term is loosely used to refer to the determinant of such a matrix. [40]

Behavior	Number of Parameters	Parameter Ordering	Restrictions
Represents a simple translation of points in the input space and has no effect on vectors or covariant vectors.	Same as the input space dimension.	The *i*-th parameter represents the translation in the *i*-th dimension.	Only defined when the input and output space has the same number of dimensions.

Table 9.3: Characteristics of the TranslationTransform class.

that the transform will have no effect whatsoever in the outcome of the process. It is just a `NULL` operation. The main characteristics of the identity transform are summarized in Table 9.2

9.6.4 Translation Transform

The `itk::TranslationTransform` is probably the simplest yet one of the most useful transformations. It maps all Points by adding a Vector to them. Vector and covariant vectors remain unchanged under this transformation since they are not associated with a particular position in space. Translation is the best transform to use when starting a registration method. Before attempting to solve for rotations or scaling it is important to overlap the anatomical objects in both images as much as possible. This is done by resolving the translational misalignment between the images. Translations also have the advantage of being fast to compute and having parameters that are easy to interpret. The main characteristics of the translation transform are presented in Table 9.3.

9.6.5 Scale Transform

The `itk::ScaleTransform` represents a simple scaling of the vector space. Different scaling factors can be applied along each dimension. Points are transformed by multiplying each one of their coordinates by the corresponding scale factor for the dimension. Vectors are transformed in the same way as points. Covariant vectors, on the other hand, are transformed differently since anisotropic scaling does not preserve angles. Covariant vectors are transformed by *dividing* their components by the scale factor of the corresponding dimension. In this way, if a covariant vector was orthogonal to a vector, this orthogonality will be preserved after the transformation. The following equations summarize the effect of the transform on the basic geometric objects.

$$\begin{array}{lccccccc} \text{Point} & \mathbf{P}' & = & T(\mathbf{P}) & : & \mathbf{P}'_{\mathbf{i}} & = & \mathbf{P_i} \cdot \mathbf{S_i} \\ \text{Vector} & \mathbf{V}' & = & T(\mathbf{V}) & : & \mathbf{V}'_{\mathbf{i}} & = & \mathbf{V_i} \cdot \mathbf{S_i} \\ \text{CovariantVector} & \mathbf{C}' & = & T(\mathbf{C}) & : & \mathbf{C}'_{\mathbf{i}} & = & \mathbf{C_i} / \mathbf{S_i} \end{array} \tag{9.2}$$

Behavior	Number of Parameters	Parameter Ordering	Restrictions
Points are transformed by multiplying each one of their coordinates by the corresponding scale factor for the dimension. Vectors are transformed as points. Covariant vectors are transformed by *dividing* their components by the scale factor in the corresponding dimension.	Same as the input space dimension.	The *i*-th parameter represents the scaling in the *i*-th dimension.	Only defined when the input and output space has the same number of dimensions.

Table 9.4: Characteristics of the ScaleTransform class.

where $\mathbf{P_i}$, $\mathbf{V_i}$ and $\mathbf{C_i}$ are the point, vector and covariant vector i-th components while $\mathbf{S_i}$ is the scaling factor along dimension $i-th$. The following equation illustrates the effect of the scaling transform on a $3D$ point.

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} S_1 & 0 & 0 \\ 0 & S_2 & 0 \\ 0 & 0 & S_3 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{9.3}$$

Scaling appears to be a simple transformation but there are actually a number of issues to keep in mind when using different scale factors along every dimension. There are subtle effects—for example, when computing image derivatives. Since derivatives are represented by covariant vectors, their values are not intuitively modified by scaling transforms.

One of the difficulties with managing scaling transforms in a registration process is that typical optimizers manage the parameter space as a vector space where addition is the basic operation. Scaling is better treated in the frame of a logarithmic space where additions result in regular multiplicative increments of the scale. Gradient descent optimizers have trouble updating step length, since the effect of an additive increment on a scale factor diminishes as the factor grows. In other words, a scale factor variation of $(1.0+\varepsilon)$ is quite different from a scale variation of $(5.0+\varepsilon)$.

Registrations involving scale transforms require careful monitoring of the optimizer parameters in order to keep it progressing at a stable pace. Note that some of the transforms discussed in following sections, for example, the AffineTransform, have hidden scaling parameters and are therefore subject

Behavior	Number of Parameters	Parameter Ordering	Restrictions
Points are transformed by multiplying each one of their coordinates by the corresponding scale factor for the dimension. Vectors are transformed as points. Covariant vectors are transformed by *dividing* their components by the scale factor in the corresponding dimension.	Same as the input space dimension.	The i-th parameter represents the scaling in the i-th dimension.	Only defined when the input and output space has the same number of dimensions. The difference between this transform and the ScaleTransform is that here the scaling factors are passed as logarithms, in this way their behavior is closer to the one of a Vector space.

Table 9.5: Characteristics of the ScaleLogarithmicTransform class.

to the same vulnerabilities of the ScaleTransform.

In cases involving misalignments with simultaneous translation, rotation and scaling components it may be desirable to solve for these components independently. The main characteristics of the scale transform are presented in Table 9.4.

9.6.6 Scale Logarithmic Transform

The `itk::ScaleLogarithmicTransform` is a simple variation of the `itk::ScaleTransform`. It is intended to improve the behavior of the scaling parameters when they are modified by optimizers. The difference between this transform and the ScaleTransform is that the parameter factors are passed here as logarithms. In this way, multiplicative variations in the scale become additive variations in the logarithm of the scaling factors.

9.6.7 Euler2DTransform

`itk::Euler2DTransform` implements a rigid transformation in $2D$. It is composed of a plane rotation and a two-dimensional translation. The rotation is applied first, followed by the translation. The following equation illustrates the effect of this transform on a $2D$ point,

Behavior	Number of Parameters	Parameter Ordering	Restrictions
Represents a $2D$ rotation and a $2D$ translation. Note that the translation component has no effect on the transformation of vectors and covariant vectors.	3	The first parameter is the angle in radians and the last two parameters are the translation in each dimension.	Only defined for two-dimensional input and output spaces.

Table 9.6: Characteristics of the Euler2DTransform class.

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} T_x \\ T_y \end{bmatrix} \tag{9.4}$$

where θ is the rotation angle and (T_x, T_y) are the components of the translation.

A challenging aspect of this transformation is the fact that translations and rotations do not form a vector space and cannot be managed as linear independent parameters. Typical optimizers make the loose assumption that parameters exist in a vector space and rely on the step length to be small enough for this assumption to hold approximately.

In addition to the non-linearity of the parameter space, the most common difficulty found when using this transform is the difference in units used for rotations and translations. Rotations are measured in radians; hence, their values are in the range $[-\pi, \pi]$. Translations are measured in millimeters and their actual values vary depending on the image modality being considered. In practice, translations have values on the order of 10 to 100. This scale difference between the rotation and translation parameters is undesirable for gradient descent optimizers because they deviate from the trajectories of descent and make optimization slower and more unstable. In order to compensate for these differences, ITK optimizers accept an array of scale values that are used to normalize the parameter space.

Registrations involving angles and translations should take advantage of the scale normalization functionality in order to obtain the best performance out of the optimizers. The main characteristics of the Euler2DTransform class are presented in Table 9.6.

9.6.8 CenteredRigid2DTransform

`itk::CenteredRigid2DTransform` implements a rigid transformation in $2D$. The main difference between this transform and the `itk::Euler2DTransform` is that here we can specify an arbitrary center of rotation, while the Euler2DTransform always uses the origin of the coordinate system as

Behavior	Number of Parameters	Parameter Ordering	Restrictions
Represents a $2D$ rotation around a user-provided center followed by a $2D$ translation.	5	The first parameter is the angle in radians. Second and third are the center of rotation coordinates and the last two parameters are the translation in each dimension.	Only defined for two-dimensional input and output spaces.

Table 9.7: Characteristics of the CenteredRigid2DTransform class.

the center of rotation. This distinction is quite important in image registration since ITK images usually have their origin in the corner of the image rather than the middle. Rotational mis-registrations usually exist, however, as rotations around the center of the image, or at least as rotations around a point in the middle of the anatomical structure captured by the image. Using gradient descent optimizers, it is almost impossible to solve non-origin rotations using a transform with origin rotations since the deep basin of the real solution is usually located across a high ridge in the topography of the cost function.

In practice, the user must supply the center of rotation in the input space, the angle of rotation and a translation to be applied after the rotation. With these parameters, the transform initializes a rotation matrix and a translation vector that together perform the equivalent of translating the center of rotation to the origin of coordinates, rotating by the specified angle, translating back to the center of rotation and finally translating by the user-specified vector.

As with the Euler2DTransform, this transform suffers from the difference in units used for rotations and translations. Rotations are measured in radians; hence, their values are in the range $[-\pi,\pi]$. The center of rotation and the translations are measured in millimeters, and their actual values vary depending on the image modality being considered. Registrations involving angles and translations should take advantage of the scale normalization functionality of the optimizers in order to get the best performance out of them.

The following equation illustrates the effect of the transform on an input point (x,y) that maps to the output point (x',y'),

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} x - C_x \\ y - C_y \end{bmatrix} + \begin{bmatrix} T_x + C_x \\ T_y + C_y \end{bmatrix} \tag{9.5}$$

where θ is the rotation angle, (C_x,C_y) are the coordinates of the rotation center and (T_x,T_y) are the components of the translation. Note that the center coordinates are subtracted before the rotation and

Behavior	Number of Parameters	Parameter Ordering	Restrictions
Represents a $2D$ rotation, homogeneous scaling and a $2D$ translation. Note that the translation component has no effect on the transformation of vectors and covariant vectors.	4	The first parameter is the scaling factor for all dimensions, the second is the angle in radians, and the last two parameters are the translations in (x,y) respectively.	Only defined for two-dimensional input and output spaces.

Table 9.8: Characteristics of the Similarity2DTransform class.

added back after the rotation. The main features of the CenteredRigid2DTransform are presented in Table 9.7.

9.6.9 Similarity2DTransform

The `itk::Similarity2DTransform` can be seen as a rigid transform combined with an isotropic scaling factor. This transform preserves angles between lines. In its $2D$ implementation, the four parameters of this transformation combine the characteristics of the `itk::ScaleTransform` and `itk::Euler2DTransform`. In particular, those relating to the non-linearity of the parameter space and the non-uniformity of the measurement units. Gradient descent optimizers should be used with caution on such parameter spaces since the notions of gradient direction and step length are ill-defined.

The following equation illustrates the effect of the transform on an input point (x,y) that maps to the output point (x',y'),

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix} \cdot \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} x - C_x \\ y - C_y \end{bmatrix} + \begin{bmatrix} T_x + C_x \\ T_y + C_y \end{bmatrix} \tag{9.6}$$

where λ is the scale factor, θ is the rotation angle, (C_x, C_y) are the coordinates of the rotation center and (T_x, T_y) are the components of the translation. Note that the center coordinates are subtracted before the rotation and scaling, and they are added back afterwards. The main features of the Similarity2DTransform are presented in Table 9.8.

A possible approach for controlling optimization in the parameter space of this transform is to dynamically modify the array of scales passed to the optimizer. The effect produced by the parameter

Behavior	Number of Parameters	Parameter Ordering	Restrictions
Represents a $3D$ rotation and a $3D$ translation. The rotation is specified as a quaternion, defined by a set of four numbers $\mathbf{q}$. The relationship between quaternion and rotation about vector $\mathbf{n}$ by angle θ is as follows: $\mathbf{q} = (\mathbf{n}\sin(\theta/\mathbf{2}), \cos(\theta/\mathbf{2}))$ Note that if the quaternion is not of unit length, scaling will also result.	7	The first four parameters defines the quaternion and the last three parameters the translation in each dimension.	Only defined for three-dimensional input and output spaces.

Table 9.9: Characteristics of the QuaternionRigidTransform class.

scaling can be used to steer the walk in the parameter space (by giving preference to some of the parameters over others). For example, perform some iterations updating only the rotation angle, then balance the array of scale factors in the optimizer and perform another set of iterations updating only the translations.

9.6.10 QuaternionRigidTransform

The `itk::QuaternionRigidTransform` class implements a rigid transformation in $3D$ space. The rotational part of the transform is represented using a quaternion while the translation is represented with a vector. Quaternions components do not form a vector space and hence raise the same concerns as the `itk::Similarity2DTransform` when used with gradient descent optimizers.

The `itk::QuaternionRigidTransformGradientDescentOptimizer` was introduced into the toolkit to address these concerns. This specialized optimizer implements a variation of a gradient descent algorithm adapted for a quaternion space. This class insures that after advancing in any direction on the parameter space, the resulting set of transform parameters is mapped back into the permissible set of parameters. In practice, this comes down to normalizing the newly-computed quaternion to make sure that the transformation remains rigid and no scaling is applied. The main characteristics of the QuaternionRigidTransform are presented in Table 9.9.

The Quaternion rigid transform also accepts a user-defined center of rotation. In this way, the transform can easily be used for registering images where the rotation is mostly relative to the center of the image instead one of the corners. The coordinates of this rotation center are not subject to

Behavior	Number of Parameters	Parameter Ordering	Restrictions
Represents a 3*D* rotation. The rotation is specified by a versor or unit quaternion. The rotation is performed around a user-specified center of rotation.	3	The three parameters define the versor.	Only defined for three-dimensional input and output spaces.

Table 9.10: Characteristics of the Versor Transform

optimization. They only participate in the computation of the mappings for Points and in the computation of the Jacobian. The transformations for Vectors and CovariantVector are not affected by the selection of the rotation center.

9.6.11 VersorTransform

By definition, a *Versor* is the rotational part of a Quaternion. It can also be defined as a *unit-quaternion* [55, 74]. Versors only have three independent components, since they are restricted to reside in the space of unit-quaternions. The implementation of versors in the toolkit uses a set of three numbers. These three numbers correspond to the first three components of a quaternion. The fourth component of the quaternion is computed internally such that the quaternion is of unit length. The main characteristics of the `itk::VersorTransform` are presented in Table 9.10.

This transform exclusively represents rotations in 3*D*. It is intended to rapidly solve the rotational component of a more general misalignment. The efficiency of this transform comes from using a parameter space of reduced dimensionality. Versors are the best possible representation for rotations in 3*D* space. Sequences of versors allow the creation of smooth rotational trajectories; for this reason, they behave stably under optimization methods.

The space formed by versor parameters is not a vector space. Standard gradient descent algorithms are not appropriate for exploring this parameter space. An optimizer specialized for the versor space is available in the toolkit under the name of `itk::VersorTransformOptimizer`. This optimizer implements versor derivatives as originally defined by Hamilton [55].

The center of rotation can be specified by the user with the `SetCenter()` method. The center is not part of the parameters to be optimized, therefore it remains the same during an optimization process. Its value is used during the computations for transforming Points and when computing the Jacobian.

Behavior	Number of Parameters	Parameter Ordering	Restrictions
Represents a 3*D* rotation and a 3*D* translation. The rotation is specified by a versor or unit quaternion, while the translation is represented by a vector. Users can specify the coordinates of the center of rotation.	6	The first three parameters define the versor and the last three parameters the translation in each dimension.	Only defined for three-dimensional input and output spaces.

Table 9.11: Characteristics of the VersorRigid3DTransform class.

9.6.12 VersorRigid3DTransform

The `itk::VersorRigid3DTransform` implements a rigid transformation in 3*D* space. It is a variant of the `itk::QuaternionRigidTransform` and the `itk::VersorTransform`. It can be seen as a `itk::VersorTransform` plus a translation defined by a vector. The advantage of this class with respect to the QuaternionRigidTransform is that it exposes only six parameters, three for the versor components and three for the translational components. This reduces the search space for the optimizer to six dimensions instead of the seven dimensional used by the QuaternionRigidTransform. This transform also allows the users to set a specific center of rotation. The center coordinates are not modified during the optimization performed in a registration process. The main features of this transform are summarized in Table 9.11. This transform is probably the best option to use when dealing with rigid transformations in 3*D*.

Given that the space of Versors is not a Vector space, typical gradient descent optimizers are not well suited for exploring the parametric space of this transform. The `itk::VersorRigid3DTranformOptimizer` has been introduced in the ITK toolkit with the purpose of providing an optimizer that is aware of the Versor space properties on the rotational part of this transform, as well as the Vector space properties on the translational part of the transform.

9.6.13 Euler3DTransform

The `itk::Euler3DTransform` implements a rigid transformation in 3*D* space. It can be seen as a rotation followed by a translation. This class exposes six parameters, three for the Euler angles that represent the rotation and three for the translational components. This transform also allows the users to set a specific center of rotation. The center coordinates are not modified during the optimization performed in a registration process. The main features of this transform are summarized in

Behavior	Number of Parameters	Parameter Ordering	Restrictions
Represents a rigid rotation in 3*D* space. That is, a rotation followed by a 3*D* translation. The rotation is specified by three angles representing rotations to be applied around the X, Y and Z axis one after another. The translation part is represented by a Vector. Users can also specify the coordinates of the center of rotation.	6	The first three parameters are the rotation angles around X, Y and Z axis, and the last three parameters are the translations along each dimension.	Only defined for three-dimensional input and output spaces.

Table 9.12: Characteristics of the Euler3DTransform class.

Table 9.12.

The fact that the three rotational parameters are non-linear and do not behave like Vector spaces must be taken into account when selecting an optimizer to work with this transform and when fine tuning the parameters of such optimizer. It is strongly recommended to use this transform by introducing very small variations on the rotational components. A small rotation will be in the range of 1 degree, which in radians is approximately 0.0.1745.

You should not expect this transform to be able to compensate for large rotations just by being driven with the optimizer. In practice you must provide a reasonable initialization of the transform angles and only need to correct for residual rotations in the order of 10 or 20 degrees.

9.6.14 Similarity3DTransform

The `itk::Similarity3DTransform` implements a similarity transformation in 3*D* space. It can be seen as an homogeneous scaling followed by a `itk::VersorRigid3DTransform`. This class exposes seven parameters, one for the scaling factor, three for the versor components and three for the translational components. This transform also allows the users to set a specific center of rotation. The center coordinates are not modified during the optimization performed in a registration process. Both the rotation and scaling operations are performed with respect to the center of rotation. The main features of this transform are summarized in Table 9.13.

Behavior	Number of Parameters	Parameter Ordering	Restrictions
Represents a $3D$ rotation, a $3D$ translation and homogeneous scaling. The scaling factor is specified by a scalar, the rotation is specified by a versor, and the translation is represented by a vector. Users can also specify the coordinates of the center of rotation, that is the same center used for scaling.	7	The first parameter is the scaling factor, the next three parameters define the versor and the last three parameters the translation in each dimension.	Only defined for three-dimensional input and output spaces.

Table 9.13: Characteristics of the Similarity3DTransform class.

The fact that the scaling and rotational spaces are non-linear and do not behave like Vector spaces must be taken into account when selecting an optimizer to work with this transform and when fine tuning the parameters of such optimizer.

9.6.15 Rigid3DPerspectiveTransform

The `itk::Rigid3DPerspectiveTransform` implements a rigid transformation in $3D$ space followed by a perspective projection. This transform is intended to be used in $3D/2D$ registration problems where a 3D object is projected onto a 2D plane. This is the case of Fluoroscopic images used for image guided intervention, and it is also the case for classical radiography. Users must provide a value for the focal distance to be used during the computation of the perspective transform. This transform also allows users to set a specific center of rotation. The center coordinates are not modified during the optimization performed in a registration process. The main features of this transform are summarized in Table 9.14. This transform is also used when creating Digitally Reconstructed Radiographs (DRRs).

The strategies for optimizing the parameters of this transform are the same ones used for optimizing the VersorRigid3DTransform. In particular, you can use the same VersorRigid3DTranform-Optimizer in order to optimize the parameters of this class.

Behavior	**Number of Parameters**	**Parameter Ordering**	**Restrictions**
Represents a rigid $3D$ transformation followed by a perspective projection. The rotation is specified by a Versor, while the translation is represented by a Vector. Users can specify the coordinates of the center of rotation. They must specifically a focal distance to be used for the perspective projection. The rotation center and the focal distance parameters are not modified during the optimization process.	6	The first three parameters define the Versor and the last three parameters the Translation in each dimension.	Only defined for three-dimensional input and two-dimensional output spaces. This is one of the few transforms where the input space has a different dimension from the output space.

Table 9.14: Characteristics of the Rigid3DPerspectiveTransform class.

Behavior	Number of Parameters	Parameter Ordering	Restrictions
Represents an affine transform composed of rotation, scaling, shearing and translation. The transform is specified by a $N \times N$ matrix and a $N \times 1$ vector where N is the space dimension.	$(N+1) \times N$	The first $N \times N$ parameters define the matrix in column-major order (where the column index varies the fastest). The last N parameters define the translations for each dimension.	Only defined when the input and output space have the same dimension.

Table 9.15: Characteristics of the AffineTransform class.

9.6.16 AffineTransform

The `itk::AffineTransform` is one of the most popular transformations used for image registration. Its main advantage comes from the fact that it is represented as a linear transformation. The main features of this transform are presented in Table 9.15.

The set of AffineTransform coefficients can actually be represented in a vector space of dimension $(N+1) \times N$. This makes it possible for optimizers to be used appropriately on this search space. However, the high dimensionality of the search space also implies a high computational complexity of cost-function derivatives. The best compromise in the reduction of this computational time is to use the transform's Jacobian in combination with the image gradient for computing the cost-function derivatives.

The coefficients of the $N \times N$ matrix can represent rotations, anisotropic scaling and shearing. These coefficients are usually of a very different dynamic range compared to the translation coefficients. Coefficients in the matrix tend to be in the range $[-1:1]$, but are not restricted to this interval. Translation coefficients, on the other hand, can be on the order of 10 to 100, and are basically related to the image size and pixel spacing.

This difference in scale makes it necessary to take advantage of the functionality offered by the optimizers for rescaling the parameter space. This is particularly relevant for optimizers based on gradient descent approaches. This transform lets the user set an arbitrary center of rotation. The coordinates of the rotation center do not make part of the parameters array passed to the optimizer. Equation 9.7 illustrates the effect of applying the AffineTransform in a point in $3D$ space.

Behavior	Number of Parameters	Parameter Ordering	Restrictions
Represents a free from deformation by providing a deformation field from the interpolation of deformations in a coarse grid.	$M \times N$	Where M is the number of nodes in the BSpline grid and N is the dimension of the space.	Only defined when the input and output space have the same dimension. This transform has the advantage of allowing to compute deformable registration. It also has the disadvantage of having a very high dimensional parametric space, and therefore requiring long computation times.

Table 9.16: Characteristics of the BSplineDeformableTransform class.

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} M_{00} & M_{01} & M_{02} \\ M_{10} & M_{11} & M_{12} \\ M_{20} & M_{21} & M_{22} \end{bmatrix} \cdot \begin{bmatrix} x - C_x \\ y - C_y \\ z - C_z \end{bmatrix} + \begin{bmatrix} T_x + C_x \\ T_y + C_y \\ T_z + C_z \end{bmatrix} \tag{9.7}$$

A registration based on the affine transform may be more effective when applied after simpler transformations have been used to remove the major components of misalignment. Otherwise it will incur an overwhelming computational cost. For example, using an affine transform, the first set of optimization iterations would typically focus on removing large translations. This task could instead be accomplished by a translation transform in a parameter space of size N instead of the $(N+1) \times N$ associated with the affine transform.

Tracking the evolution of a registration process that uses AffineTransforms can be challenging, since it is difficult to represent the coefficients in a meaningful way. A simple printout of the transform coefficients generally does not offer a clear picture of the current behavior and trend of the optimization. A better implementation uses the affine transform to deform wire-frame cube which is shown in a $3D$ visualization display.

9.6.17 BSplineDeformableTransform

The `itk::BSplineDeformableTransform` is designed to be used for solving deformable registration problems. This transform is equivalent to generation a deformation field where a deformation vector is assigned to every point in space. The deformation vectors are computed using BSpline interpolation from the deformation values of points located in a coarse grid, that is usually referred to as the BSpline grid.

The BSplineDeformableTransform is not flexible enough for accounting for large rotations or shear-

ing, or scaling differences. In order to compensate for this limitation, it provides the functionality of being composed with an arbitrary transform. This transform is known as the *Bulk* transform and it is applied to points before they are mapped with the displacement field.

This transform do not provide functionalities for mapping Vectors nor CovariantVectors, only Points can be mapped. The reason is that the variations of a vector under a deformable transform actually depend on the location of the vector in space. In other words, Vector only make sense as the relative position between two points.

The BSplineDeformableTransform has a very large number of parameters and therefore is well suited for the `itk::LBFGSOptimizer` and `itk::LBFGSBOptimizer`. The use of this transform for was proposed in the following papers [120, 92, 93].

9.6.18 KernelTransforms

Kernel Transforms are a set of Transforms that are also suitable for performing deformable registration. These transforms compute on the fly the displacements corresponding to a deformation field. The displacement values corresponding to every point in space are computed by interpolation from the vectors defined by a set of *Source Landmarks* and a set of *Target Landmarks*.

Several variations of these transforms are available in the toolkit. They differ on the type of interpolation kernel that is used when computing the deformation in a particular point of space. Note that these transforms are computationally expensive and that their numerical complexity is proportional to the number of landmarks and the space dimension.

The following is the list of Transforms based on the KernelTransform.

- `itk::ElasticBodySplineKernelTransform`
- `itk::ElasticBodyReciprocalSplineKernelTransform`
- `itk::ThinPlateSplineKernelTransform`
- `itk::ThinPlateR2LogRSplineKernelTransform`
- `itk::VolumeSplineKernelTransform`

Details about the mathematical background of these transform can be found in the paper by Davis *et. al* [33] and the papers by Rohr *et. al* [117, 118].

9.7 Metrics

In OTB, `itk::ImageToImageMetric` objects quantitatively measure how well the transformed moving image fits the fixed image by comparing the gray-scale intensity of the images. These metrics are very flexible and can work with any transform or interpolation method and do not require reduction of the gray-scale images to sparse extracted information such as edges.

The metric component is perhaps the most critical element of the registration framework. The selection of which metric to use is highly dependent on the registration problem to be solved. For example, some metrics have a large capture range while others require initialization close to the optimal position. In addition, some metrics are only suitable for comparing images obtained from the same type of sensor, while others can handle multi-sensor comparisons. Unfortunately, there are no clear-cut rules as to how to choose a metric.

The basic inputs to a metric are: the fixed and moving images, a transform and an interpolator. The method `GetValue()` can be used to evaluate the quantitative criterion at the transform parameters specified in the argument. Typically, the metric samples points within a defined region of the fixed image. For each point, the corresponding moving image position is computed using the transform with the specified parameters, then the interpolator is used to compute the moving image intensity at the mapped position.

The metrics also support region based evaluation. The `SetFixedImageMask()` and `SetMovingImageMask()` methods may be used to restrict evaluation of the metric within a specified region. The masks may be of any type derived from `itk::SpatialObject`.

Besides the measure value, gradient-based optimization schemes also require derivatives of the measure with respect to each transform parameter. The methods `GetDerivatives()` and `GetValueAndDerivatives()` can be used to obtain the gradient information.

The following is the list of metrics currently available in OTB:

- Mean squares
  `itk::MeanSquaresImageToImageMetric`
- Normalized correlation
  `itk::NormalizedCorrelationImageToImageMetric`
- Mean reciprocal squared difference
  `itk::MeanReciprocalSquareDifferenceImageToImageMetric`
- Mutual information by Viola and Wells
  `itk::MutualInformationImageToImageMetric`
- Mutual information by Mattes
  `itk::MattesMutualInformationImageToImageMetric`
- Kullback Liebler distance metric by Kullback and Liebler
  `itk::KullbackLeiblerCompareHistogramImageToImageMetric`

- Normalized mutual information
  `itk::NormalizedMutualInformationHistogramImageToImageMetric`
- Mean squares histogram
  `itk::MeanSquaresHistogramImageToImageMetric`
- Correlation coefficient histogram
  `itk::CorrelationCoefficientHistogramImageToImageMetric`
- Cardinality Match metric
  `itk::MatchCardinalityImageToImageMetric`
- Kappa Statistics metric
  `itk::KappaStatisticImageToImageMetric`
- Gradient Difference metric
  `itk::GradientDifferenceImageToImageMetric`

In the following sections, we describe each metric type in detail. For ease of notation, we will refer to the fixed image $f(\mathbf{X})$ and transformed moving image $(m \circ T(\mathbf{X}))$ as images A and B.

9.7.1 Mean Squares Metric

The `itk::MeanSquaresImageToImageMetric` computes the mean squared pixel-wise difference in intensity between image A and B over a user defined region:

$$MS(A,B) = \frac{1}{N}\sum_{i=1}^{N}(A_i - B_i)^2 \tag{9.8}$$

A_i is the i-th pixel of Image A
B_i is the i-th pixel of Image B
N is the number of pixels considered

The optimal value of the metric is zero. Poor matches between images A and B result in large values of the metric. This metric is simple to compute and has a relatively large capture radius.

This metric relies on the assumption that intensity representing the same homologous point must be the same in both images. Hence, its use is restricted to images of the same modality. Additionally, any linear changes in the intensity result in a poor match value.

Exploring a Metric

Getting familiar with the characteristics of the Metric as a cost function is fundamental in order to find the best way of setting up an optimization process that will use this metric for solving a registration problem.

9.7.2 Normalized Correlation Metric

The `itk::NormalizedCorrelationImageToImageMetric` computes pixel-wise cross-correlation and normalizes it by the square root of the autocorrelation of the images:

$$NC(A,B) = -1 \times \frac{\sum_{i=1}^{N}(A_i \cdot B_i)}{\sqrt{\sum_{i=1}^{N} A_i^2 \cdot \sum_{i=1}^{N} B_i^2}} \tag{9.9}$$

A_i is the i-th pixel of Image A
B_i is the i-th pixel of Image B
N is the number of pixels considered

Note the -1 factor in the metric computation. This factor is used to make the metric be optimal when its minimum is reached. The optimal value of the metric is then minus one. Misalignment between the images results in small measure values. The use of this metric is limited to images obtained using the same imaging modality. The metric is insensitive to multiplicative factors – illumination changes – between the two images. This metric produces a cost function with sharp peaks and well defined minima. On the other hand, it has a relatively small capture radius.

9.7.3 Mean Reciprocal Square Differences

The `itk::MeanReciprocalSquareDifferenceImageToImageMetric` computes pixel-wise differences and adds them after passing them through a bell-shaped function $\frac{1}{1+x^2}$:

$$PI(A,B) = \sum_{i=1}^{N} \frac{1}{1 + \frac{(A_i - B_i)^2}{\lambda^2}} \tag{9.10}$$

A_i is the i-th pixel of Image A
B_i is the i-th pixel of Image B
N is the number of pixels considered
λ controls the capture radius

The optimal value is N and poor matches results in small measure values. The characteristics of this metric have been studied by Penney and Holden [58][105].

This image metric has the advantage of producing poor values when few pixels are considered. This makes it consistent when its computation is subject to the size of the overlap region between the images. The capture radius of the metric can be regulated with the parameter λ. The profile of this metric is very peaky. The sharp peaks of the metric help to measure spatial misalignment with high precision. Note that the notion of capture radius is used here in terms of the intensity domain, not

the spatial domain. In that regard, λ should be given in intensity units and be associated with the differences in intensity that will make drop the metric by 50%.

The metric is limited to images of the same image modality. The fact that its derivative is large at the central peak is a problem for some optimizers that rely on the derivative to decrease as the extrema are reached. This metric is also sensitive to linear changes in intensity.

9.7.4 Mutual Information Metric

The `itk::MutualInformationImageToImageMetric` computes the mutual information between image A and image B. Mutual information (MI) measures how much information one random variable (image intensity in one image) tells about another random variable (image intensity in the other image). The major advantage of using MI is that the actual form of the dependency does not have to be specified. Therefore, complex mapping between two images can be modeled. This flexibility makes MI well suited as a criterion of multi-modality registration [109].

Mutual information is defined in terms of entropy. Let

$$H(A) = -\int p_A(a) \log p_A(a)\, da \tag{9.11}$$

be the entropy of random variable A, $H(B)$ the entropy of random variable B and

$$H(A,B) = \int p_{AB}(a,b) \log p_{AB}(a,b)\, da\, db \tag{9.12}$$

be the joint entropy of A and B. If A and B are independent, then

$$p_{AB}(a,b) = p_A(a) p_B(b) \tag{9.13}$$

and

$$H(A,B) = H(A) + H(B). \tag{9.14}$$

However, if there is any dependency, then

$$H(A,B) < H(A) + H(B). \tag{9.15}$$

The difference is called Mutual Information : $I(A,B)$

$$I(A,B) = H(A) + H(B) - H(A,B) \tag{9.16}$$

Parzen Windowing

In a typical registration problem, direct access to the marginal and joint probability densities is not available and hence the densities must be estimated from the image data. Parzen windows (also known as kernel density estimators) can be used for this purpose. In this scheme, the densities are constructed by taking intensity samples S from the image and superpositioning kernel functions $K(\cdot)$ centered on the elements of S as illustrated in Figure 9.16:

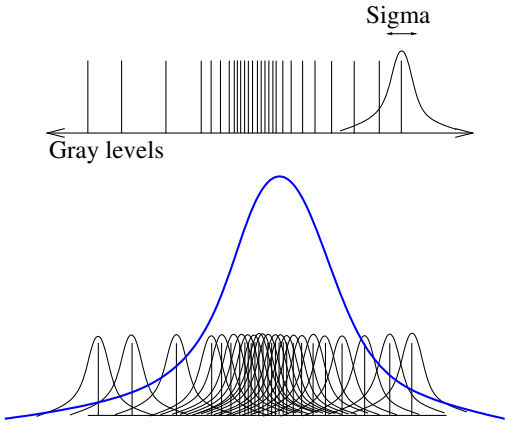


Figure 9.16: In Parzen windowing, a continuous density function is constructed by superimposing kernel functions (Gaussian function in this case) centered on the intensity samples obtained from the image.

A variety of functions can be used as the smoothing kernel with the requirement that they are smooth, symmetric, have zero mean and integrate to one. For example, boxcar, Gaussian and B-spline functions are suitable candidates. A smoothing parameter is used to scale the kernel function. The larger the smoothing parameter, the wider the kernel function used and hence the smoother the density estimate. If the parameter is too large, features such as modes in the density will get smoothed out. On the other hand, if the smoothing parameter is too small, the resulting density may be too noisy. The estimation is given by the following equation.

$$p(a) \approx P^*(a) = \frac{1}{N} \sum_{s_j \in S} K(a - s_j) \tag{9.17}$$

Choosing the optimal smoothing parameter is a difficult research problem and beyond the scope of this software guide. Typically, the optimal value of the smoothing parameter will depend on the data and the number of samples used.

Viola and Wells Implementation

OTB, through ITK, has multiple implementations of the mutual information metric. One of the most commonly used is `itk::MutualInformationImageToImageMetric` and follows the method specified by Viola and Wells in [134].

In this implementation, two separate intensity samples S and R are drawn from the image: the first to compute the density, and the second to approximate the entropy as a sample mean:

$$H(A) = \frac{1}{N} \sum_{r_j \in R} \log P^*(r_j). \tag{9.18}$$

Gaussian density is used as a smoothing kernel, where the standard deviation σ acts as the smoothing parameter.

The number of spatial samples used for computation is defined using the `SetNumberOfSpatialSamples()` method. Typical values range from 50 to 100. Note that computation involves an $N \times N$ loop and hence, the computation burden becomes very expensive when a large number of samples is used.

The quality of the density estimates depends on the choice of the standard deviation of the Gaussian kernel. The optimal choice will depend on the content of the images. In our experience with the toolkit, we have found that a standard deviation of 0.4 works well for images that have been normalized to have a mean of zero and standard deviation of 1.0. The standard deviation of the fixed image and moving image kernel can be set separately using methods `SetFixedImageStandardDeviation()` and `SetMovingImageStandardDeviation()`.

Mattes et al. Implementation

Another form of mutual information metric available in ITK follows the method specified by Mattes et al. in [92] and is implemented by the `itk::MattesMutualInformationImageToImageMetric` class.

In this implementation, only one set of intensity samples is drawn from the image. Using this set, the marginal and joint probability density function (PDF) is evaluated at discrete positions or bins uniformly spread within the dynamic range of the images. Entropy values are then computed by summing over the bins.

The number of spatial samples used is set using method `SetNumberOfSpatialSamples()`. The number of bins used to compute the entropy values is set via `SetNumberOfHistogramBins()`.

Since the fixed image PDF does not contribute to the metric derivatives, it does not need to be smooth. Hence, a zero order (boxcar) B-spline kernel is used for computing the PDF. On the other hand, to ensure smoothness, a third order B-spline kernel is used to compute the moving image intensity PDF. The advantage of using a B-spline kernel over a Gaussian kernel is that the B-spline kernel has a finite support region. This is computationally attractive, as each intensity sample only affects a small number of bins and hence does not require a $N \times N$ loop to compute the metric value.

During the PDF calculations, the image intensity values are linearly scaled to have a minimum of zero and maximum of one. This rescaling means that a fixed B-spline kernel bandwidth of one can be used to handle image data with arbitrary magnitude and dynamic range.

9.7.5 Kullback-Leibler distance metric

The `itk::KullbackLeiblerCompareHistogramImageToImageMetric` is yet another information based metric. Kullback-Leibler distance measures the relative entropy between two discrete probability distributions. The distributions are obtained from the histograms of the two input images, A and B.

The Kullback-Liebler distance between two histograms is given by

$$KL(A,B) = \sum_{i}^{N} p_A(i) \times \log \frac{p_A(i)}{p_B(i)} \tag{9.19}$$

The distance is always non-negative and is zero only if the two distributions are the same. Note that the distance is not symmetric. In other words, $KL(A,B) \neq KL(B,A)$. Nevertheless, if the distributions are not too dissimilar, the difference between $KL(A,B)$ and $KL(B,A)$ is small.

The implementation in ITK is based on [25].

9.7.6 Normalized Mutual Information Metric

Given two images, A and B, the normalized mutual information may be computed as

$$NMI(A,B) = 1 + \frac{I(A,B)}{H(A,B)} = \frac{H(A)+H(B)}{H(A,B)} \tag{9.20}$$

where the entropy of the images, $H(A)$, $H(B)$, the mutual information, $I(A,B)$ and the joint entropy $H(A,B)$ are computed as mentioned in 9.7.4. Details of the implementation may be found in the [54].

9.7.7 Mean Squares Histogram

The `itk::MeanSquaresHistogramImageToImageMetric` is an alternative implementation of the Mean Squares Metric. In this implementation the joint histogram of the fixed and the mapped moving image is built first. The user selects the number of bins to use in this joint histogram. Once the joint histogram is computed, the bins are visited with an iterator. Given that each bin is associated to a pair of intensities of the form: $\{$fixed intensity, moving intensity$\}$, along with the number of pixels pairs in the images that fell in this bin, it is then possible to compute the sum of square distances between the intensities of both images at the quantization levels defined by the joint histogram bins.

This metric can be represented with Equation 9.21

$$MSH = \sum_{f} \sum_{m} H(f,m)(f-m)^2 \tag{9.21}$$

where $H(f,m)$ is the count on the joint histogram bin identified with fixed image intensity f and moving image intensity m.

9.7.8 Correlation Coefficient Histogram

The `itk::CorrelationCoefficientHistogramImageToImageMetric` computes the cross correlation coefficient between the intensities in the fixed image and the intensities on the mapped moving image. This metric is intended to be used in images of the same modality where the relationship between the intensities of the fixed image and the intensities on the moving images is given by a linear equation.

The correlation coefficient is computed from the Joint histogram as

$$CC = \frac{\sum_f \sum_m H(f,m)\left(f \cdot m - \overline{f} \cdot \overline{m}\right)}{\sum_f H(f)\left((f-\overline{f})^2\right) \cdot \sum_m H(m)\left((m-\overline{m})^2\right)} \tag{9.22}$$

Where $H(f,m)$ is the joint histogram count for the bin identified with the fixed image intensity f and the moving image intensity m. The values $\overline{f}$ and $\overline{m}$ are the mean values of the fixed and moving images respectively. $H(f)$ and $H(m)$ are the histogram counts of the fixed and moving images respectively. The optimal value of the correlation coefficient is 1, which would indicate a perfect straight line in the histogram.

9.7.9 Cardinality Match Metric

The `itk::MatchCardinalityImageToImageMetric` computes cardinality of the set of pixels that match exactly between the moving and fixed images. In other words, it computes the number of pixel matches and mismatches between the two images. The match is designed for label maps. All pixel mismatches are considered equal whether they are between label 1 and label 2 or between label 1 and label 500. In other words, the magnitude of an individual label mismatch is not relevant, or the occurrence of a label mismatch is important.

The spatial correspondence between the fixed and moving images is established using a `itk::Transform` using the `SetTransform()` method and an interpolator using `SetInterpolator()`. Given that we are matching pixels with labels, it is advisable to use Nearest Neighbor interpolation.

9.7.10 Kappa Statistics Metric

The `itk::KappaStatisticImageToImageMetric` computes spatial intersection of two binary images. The metric here is designed for matching pixels in two images with the same exact value, which may be set using `SetForegroundValue()`. Given two images A and B, the κ coefficient is computed as

$$\kappa = \frac{|A| \cap |B|}{|A| + |B|} \tag{9.23}$$

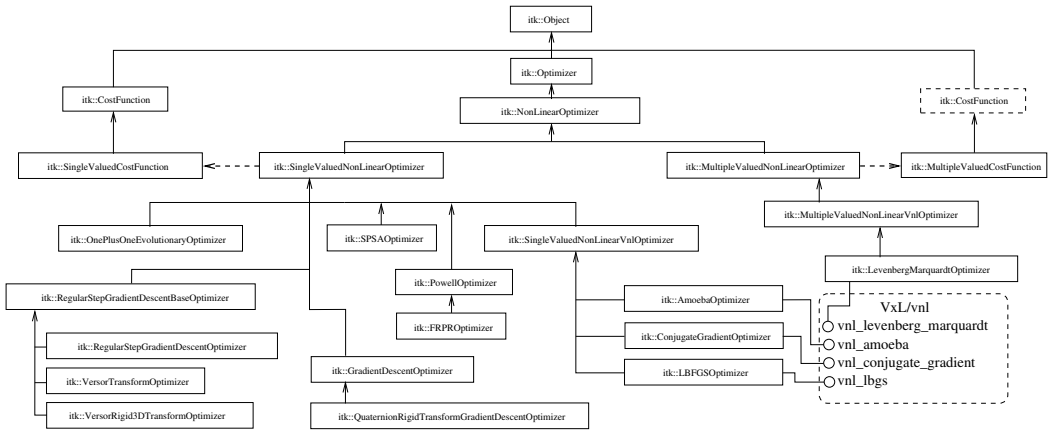


Figure 9.17: Class diagram of the optimizers hierarchy.

where $|A|$ is the number of foreground pixels in image A. This computes the fraction of area in the two images that is common to both the images. In the computation of the metric, only foreground pixels are considered.

9.7.11 Gradient Difference Metric

This `itk::GradientDifferenceImageToImageMetric` metric evaluates the difference in the derivatives of the moving and fixed images. The derivatives are passed through a function $\frac{1}{1+x}$ and then they are added. The purpose of this metric is to focus the registration on the edges of structures in the images. In this way the borders exert larger influence on the result of the registration than do the inside of the homogeneous regions on the image.

9.8 Optimizers

Optimization algorithms are encapsulated as `itk::Optimizer` objects within OTB. Optimizers are generic and can be used for applications other than registration. Within the registration framework, subclasses of `itk::SingleValuedNonLinearOptimizer` are used to optimize the metric criterion with respect to the transform parameters.

The basic input to an optimizer is a cost function object. In the context of registration, `itk::ImageToImageMetric` classes provides this functionality. The initial parameters are set using `SetInitialPosition()` and the optimization algorithm is invoked by `StartOptimization()`. Once the optimization has finished, the final parameters can be obtained using `GetCurrentPosition()`.

Some optimizers also allow rescaling of their individual parameters. This is convenient for normalizing parameters spaces where some parameters have different dynamic ranges. For example, the first parameter of `itk::Euler2DTransform` represents an angle while the last two parameters represent translations. A unit change in angle has a much greater impact on an image than a unit change in translation. This difference in scale appears as long narrow valleys in the search space making the optimization problem more difficult. Rescaling the translation parameters can help to fix this problem. Scales are represented as an `itk::Array` of doubles and set defined using `SetScales()`.

There are two main types of optimizers in OTB. In the first type we find optimizers that are suitable for dealing with cost functions that return a single value. These are indeed the most common type of cost functions, and are known as *Single Valued* functions, therefore the corresponding optimizers are known as *Single Valued* optimizers. The second type of optimizers are those suitable for managing cost functions that return multiple values at each evaluation. These cost functions are common in model-fitting problems and are known as *Multi Valued* or *Multivariate* functions. The corresponding optimizers are therefore called *MultipleValued* optimizers in OTB.

The `itk::SingleValuedNonLinearOptimizer` is the base class for the first type of optimizers while the `itk::MultipleValuedNonLinearOptimizer` is the base class for the second type of optimizers.

The types of single valued optimizer currently available in OTB are:

- **Amoeba**: Nelder-Meade downhill simplex. This optimizer is actually implemented in the `vxl/vnl` numerics toolkit. The ITK class `itk::AmoebaOptimizer` is merely an adaptor class.
- **Conjugate Gradient**: Fletcher-Reeves form of the conjugate gradient with or without preconditioning (`itk::ConjugateGradientOptimizer`). It is also an adaptor to an optimizer in `vnl`.
- **Gradient Descent**: Advances parameters in the direction of the gradient where the step size is governed by a learning rate (`itk::GradientDescentOptimizer`).
- **Quaternion Rigid Transform Gradient Descent**: A specialized version of GradientDescentOptimizer for QuaternionRigidTransform parameters, where the parameters representing the quaternion are normalized to a magnitude of one at each iteration to represent a pure rotation (`itk::QuaternionRigidTransformGradientDescent`).
- **LBFGS**: Limited memory Broyden, Fletcher, Goldfarb and Shannon minimization. It is an adaptor to an optimizer in `vnl` (`itk::LBFGSOptimizer`).
- **LBFGSB**: A modified version of the LBFGS optimizer that allows to specify bounds for the parameters in the search space. It is an adaptor to an optimizer in `netlib`. Details on this optimizer can be found in [18, 19] (`itk::LBFGSBOptimizer`).
- **One Plus One Evolutionary**: Strategy that simulates the biological evolution of a set of samples in the search space (`itk::OnePlusOneEvolutionaryOptimizer.`). Details on this optimizer can be found in [127].

- **Regular Step Gradient Descent**: Advances parameters in the direction of the gradient where a bipartition scheme is used to compute the step size (`itk::RegularStepGradientDescentOptimizer`).
- **Powell Optimizer**: Powell optimization method. For an N-dimensional parameter space, each iteration minimizes(maximizes) the function in N (initially orthogonal) directions. This optimizer is described in [111]. (`itk::PowellOptimizer`).
- **SPSA Optimizer**: Simultaneous Perturbation Stochastic Approximation Method. This optimizer is described in `http://www.jhuapl.edu/SPSA` and in [125]. (`itk::SPSAOptimizer`).
- **Versor Transform Optimizer**: A specialized version of the RegularStepGradientDescentOptimizer for VersorTransform parameters, where the current rotation is composed with the gradient rotation to produce the new rotation versor. It follows the definition of versor gradients defined by Hamilton [55] (`itk::VersorTransformOptimizer`).
- **Versor Rigid3D Transform Optimizer**: A specialized version of the RegularStepGradientDescentOptimizer for VersorRigid3DTransform parameters, where the current rotation is composed with the gradient rotation to produce the new rotation versor. The translational part of the transform parameters are updated as usually done in a vector space. (`itk::VersorRigid3DTransformOptimizer`).

A parallel hierarchy exists for optimizing multiple-valued cost functions. The base optimizer in this branch of the hierarchy is the `itk::MultipleValuedNonLinearOptimizer` whose only current derived class is:

- **Levenberg Marquardt**: Non-linear least squares minimization. Adapted to an optimizer in `vnl` (`itk::LevenbergMarquardtOptimizer`). This optimizer is described in [111].

Figure 9.17 illustrates the full class hierarchy of optimizers in OTB. Optimizers in the lower right corner are adaptor classes to optimizers existing in the `vxl/vnl` numerics toolkit. The optimizers interact with the `itk::CostFunction` class. In the registration framework this cost function is reimplemented in the form of ImageToImageMetric.

9.9 Landmark-based registration

CHAPTER

TEN

DISPARITY MAP ESTIMATION

This chapter introduces the tools available in OTB for the estimation of geometric disparities between images.

10.1 Disparity Maps

The problem we want to deal with is the one of the automatic disparity map estimation of images acquired with different sensors. By different sensors, we mean sensors which produce images with different radiometric properties, that is, sensors which measure different physical magnitudes: optical sensors operating in different spectral bands, radar and optical sensors, etc.

For this kind of image pairs, the classical approach of fine correlation [81, 43], can not always be used to provide the required accuracy, since this similarity measure (the correlation coefficient) can only measure similarities up to an affine transformation of the radiometries.

There are two main questions which can be asked about what we want to do:

1. Can we define what the similarity is between, for instance, a radar and an optical image?
2. What does *fine registration* mean in the case where the geometric distortions are so big and the source of information can be located in different places (for instance, the same edge can be produced by the edge of the roof of a building in an optical image and by the wall-ground bounce in a radar image)?

We can answer by saying that the images of the same object obtained by different sensors are two different representations of the same reality. For the same spatial location, we have two different measures. Both informations come from the same source and thus they have a lot of common information. This relationship may not be perfect, but it can be evaluated in a relative way: different

geometrical distortions are compared and the one leading to the strongest link between the two measures is kept.

When working with images acquired with the same (type of) sensor one can use a very effective approach. Since a correlation coefficient measure is robust and fast for similar images, one can afford to apply it in every pixel of one image in order to search for the corresponding HP in the other image. One can thus build a deformation grid (a sampling of the deformation map). If the sampling step of this grid is short enough, the interpolation using an analytical model is not needed and high frequency deformations can be estimated. The obtained grid can be used as a re-sampling grid and thus obtain the registered images.

No doubt, this approach, combined with image interpolation techniques (in order to estimate sub-pixel deformations) and multi-resolution strategies allows for obtaining the best performances in terms of deformation estimation, and hence for the automatic image registration.

Unfortunately, in the multi-sensor case, the correlation coefficient can not be used. We will thus try to find similarity measures which can be applied in the multi-sensor case with the same approach as the correlation coefficient.

We start by giving several definitions which allow for the formalization of the image registration problem. First of all, we define the master image and the slave image:

Definition 1 *Master image: image to which other images will be registered; its geometry is considered as the reference.*

Definition 2 *Slave image: image to be geometrically transformed in order to be registered to the master image.*

Two main concepts are the one of *similarity measure* and the one of *geometric transformation*:

Definition 3 *Let I and J be two images and let c a similarity criterion, we call similarity measure any scalar, strictly positive function*

$$S_c(I,J) = f(I,J,c). \tag{10.1}$$

S_c has an absolute maximum when the two images I and J are identical in the sense of the criterion c.

Definition 4 *A geometric transformation T is an operator which, applied to the coordinates (x,y) of a point in the slave image, gives the coordinates (u,v) of its HP in the master image:*

$$\begin{pmatrix} u \\ v \end{pmatrix} = T \begin{pmatrix} x \\ y \end{pmatrix} \tag{10.2}$$

Finally we introduce a definition for the image registration problem:

Definition 5 *Registration problem:*

1. *determine a geometric transformation T which maximizes the similarity between a master image I and the result of the transformation $T \circ J$:*

$$Arg \max_{T}(S_c(I, T \circ J)); \tag{10.3}$$

2. *re-sampling of J by applying T.*

10.1.1 Geometric deformation modeling

The geometric transformation of definition 4 is used for the correction of the existing deformation between the two images to be registered. This deformation contains informations which are linked to the observed scene and the acquisition conditions. They can be classified into 3 classes depending on their physical source:

1. deformations linked to the mean attitude of the sensor (incidence angle, presence or absence of yaw steering, etc.);
2. deformations linked to a stereo vision (mainly due to the topography);
3. deformations linked to attitude evolution during the acquisition (vibrations which are mainly present in push-broom sensors).

These deformations are characterized by their spatial frequencies and intensities which are summarized in table 10.1.

Depending on the type of deformation to be corrected, its model will be different. For example, if the only deformation to be corrected is the one introduced by the mean attitude, a physical model

	Intensity	Spatial Frequency
Mean Attitude	Strong	Low
Stereo	Medium	High and Medium
Attitude evolution	Low	Low to Medium

Table 10.1: Characterization of the geometric deformation sources

for the acquisition geometry (independent of the image contents) will be enough. If the sensor is not well known, this deformation can be approximated by a simple analytical model. When the deformations to be modeled are high frequency, analytical (parametric) models are not suitable for a fine registration. In this case, one has to use a fine sampling of the deformation, that means the use of deformation grids. These grids give, for a set of pixels of the master image, their location in the slave image.

The following points summarize the problem of the deformation modeling:

1. An analytical model is just an approximation of the deformation. It is often obtained as follows:
   (a) Directly from a physical model without using any image content information.
   (b) By estimation of the parameters of an a priori model (polynomial, affine, etc.). These parameters can be estimated:
      i. Either by solving the equations obtained by taking HP. The HP can be manually or automatically extracted.
      ii. Or by maximization of a global similarity measure.
2. A deformation grid is a sampling of the deformation map.

The last point implies that the sampling period of the grid must be short enough in order to account for high frequency deformations (Shannon theorem). Of course, if the deformations are non stationary (it is usually the case of topographic deformations), the sampling can be irregular.

As a conclusion, we can say that definition 5 poses the registration problem as an optimization problem. This optimization can be either global or local with a similarity measure which can also be either local or global. All this is synthesized in table 10.2.

Geometric model	Similarity measure	Optimization of the deformation
Physical model	None	Global
Analytical model with a priori HP	Local	Global
Analytical model without a priori HP	Global	Global
Grid	Local	Local

Table 10.2: Approaches to image registration

The ideal approach would consist in a registration which is locally optimized, both in similarity and deformation, in order to have the best registration quality. This is the case when deformation grids with dense sampling are used. Unfortunately, this case is the most computationally heavy and one often uses either a low sampling rate of the grid, or the evaluation of the similarity in a small set of pixels for the estimation of an analytical model. Both of these choices lead to local registration errors which, depending on the topography, can amount several pixels.

Even if this registration accuracy can be enough in many applications, (ortho-registration, import into a GIS, etc.), it is not acceptable in the case of data fusion, multi-channel segmentation or change detection [130]. This is why we will focus on the problem of deformation estimation using dense grids.

10.1.2 Similarity measures

The fine modeling of the geometric deformation we are looking for needs for the estimation of the coordinates of nearly every pixel in the master image inside the slave image. In the classical mono-sensor case where we use the correlation coefficient we proceed as follows.

The geometric deformation is modeled by local rigid displacements. One wants to estimate the coordinates of each pixel of the master image inside the slave image. This can be represented by a displacement vector associated to every pixel of the master image. Each of the two components (lines and columns) of this vector field will be called deformation grid.

We use a small window taken in the master image and we test the similarity for every possible shift within an exploration area inside the slave image (figure 10.1).

That means that for each position we compute the correlation coefficient. The result is a correlation surface whose maximum gives the most likely local shift between both images:

$$\rho_{I,J}(\Delta x, \Delta y) = \frac{1}{N} \frac{\sum_{x,y}(I(x,y) - m_I)(J(x+\Delta x, y+\Delta y) - m_J)}{\sigma_I \sigma_J}. \tag{10.4}$$

In this expression, N is the number of pixels of the analysis window, m_I and m_J are the estimated mean values inside the analysis window of respectively image I and image J and σ_I and σ_J are their standard deviations.

Quality criteria can be applied to the estimated maximum in order to give a confidence factor to

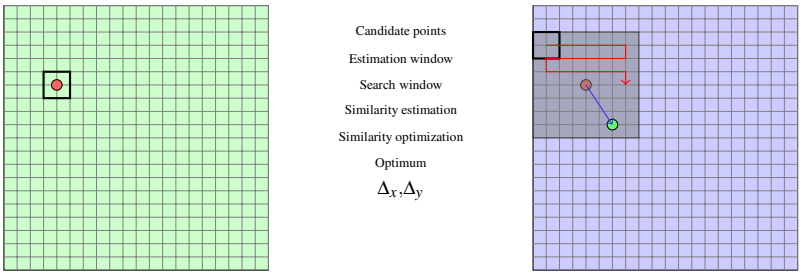


Figure 10.1: Estimation of the correlation surface.

the estimated shift: width of the peak, maximum value, etc. Sub-pixel shifts can be measured by applying fractional shifts to the sliding window. This can be done by image interpolation.

The interesting parameters of the procedure are:

- The size of the exploration area: it determines the computational load of the algorithm (we want to reduce it), but it has to be large enough in order to cope with large deformations.
- The size of the sliding window: the robustness of the correlation coefficient estimation increases with the window size, but the hypothesis of local rigid shifts may not be valid for large windows.

The correlation coefficient cannot be used with original grey-level images in the multi-sensor case. It could be used on extracted features (edges, etc.), but the feature extraction can introduce localization errors. Also, when the images come from sensors using very different modalities, it can be difficult to find similar features in both images. In this case, one can try to find the similarity at the pixel level, but with other similarity measures and apply the same approach as we have just described.

The concept of similarity measure has been presented in definition 3. The difficulty of the procedure lies in finding the function f which properly represents the criterion c. We also need that f be easily and robustly estimated with small windows. We extend here what we proposed in [67].

10.1.3 The correlation coefficient

We remind here the computation of the correlation coefficient between two image windows I and J. The coordinates of the pixels inside the windows are represented by (x,y):

$$\rho(I,J) = \frac{1}{N}\frac{\sum_{x,y}(I(x,y)-m_I)(J(x,y)-m_J)}{\sigma_I\sigma_J}. \tag{10.5}$$

In order to qualitatively characterize the different similarity measures we propose the following experiment. We take two images which are perfectly registered and we extract a small window of size $N \times M$ from each of the images (this size is set to 101×101 for this experiment). For the master image, the window will be centered on coordinates (x_0, y_0) (the center of the image) and for the slave image, it will be centered on coordinates $(x_0 + \Delta x, y_0)$. With different values of Δx (from -10 pixels to 10 pixels in our experiments), we obtain an estimate of $\rho(I,J)$ as a function of Δx, which we write as $\rho(\Delta x)$ for short. The obtained curve should have a maximum for $\Delta x = 0$, since the images are perfectly registered. We would also like to have an absolute maximum with a high value and with a sharp peak, in order to have a good precision for the shift estimate.

10.2 Regular grid disparity map estimation

The source code for this example can be found in the file
`Examples/DisparityMap/FineRegistrationImageFilterExample.cxx`.

This example demonstrates the use of the `otb::FineRegistrationImageFilter`. This filter performs deformation estimation using the classical extrema of image-to-image metric look-up in a search window.

The first step toward the use of these filters is to include the proper header files.

```
#include "otbFineRegistrationImageFilter.h"
```

Several type of `otb::Image` are required to represent the input image, the metric field, and the deformation field.

```
typedef otb::Image<PixelType, ImageDimension> InputImageType;
typedef otb::Image<PixelType, ImageDimension> MetricImageType;
typedef otb::Image<DisplacementPixelType,
    ImageDimension>                           DisplacementFieldType;
```

To make the metric estimation more robust, the first required step is to blur the input images. This is done using the `itk::RecursiveGaussianImageFilter`:

```
typedef itk::RecursiveGaussianImageFilter<InputImageType,
    InputImageType> InputBlurType;
```

```
InputBlurType::Pointer fBlur = InputBlurType::New();
fBlur->SetInput(fReader->GetOutput());
fBlur->SetSigma(atof(argv[7]));

InputBlurType::Pointer mBlur = InputBlurType::New();
mBlur->SetInput(mReader->GetOutput());
mBlur->SetSigma(atof(argv[7]));
```

Now, we declare and instantiate the `otb::FineCorrelationImageFilter` which is going to perform the registration:

```
typedef otb::FineRegistrationImageFilter<InputImageType,
    MetricImageType,
    DisplacementFieldType>
RegistrationFilterType;

RegistrationFilterType::Pointer registrator = RegistrationFilterType::New();

registrator->SetMovingInput(mBlur->GetOutput());
registrator->SetFixedInput(fBlur->GetOutput());
```

Some parameters need to be specified to the filter:

- The area where the search is performed. This area is defined by its radius:

```
typedef RegistrationFilterType::SizeType RadiusType;

RadiusType searchRadius;

searchRadius[0] = atoi(argv[8]);
searchRadius[1] = atoi(argv[8]);

registrator->SetSearchRadius(searchRadius);
```

- The window used to compute the local metric. This window is also defined by its radius:

```
RadiusType metricRadius;
metricRadius[0] = atoi(argv[9]);
metricRadius[1] = atoi(argv[9]);

registrator->SetRadius(metricRadius);
```

We need to set the sub-pixel accuracy we want to obtain:

The default matching metric used by the `FineRegistrationImageFilter::is` standard correlation. However, we may also use any other image-to-image metric provided by ITK. For instance, here is how we would use the `itk::MutualInformationImageToImageMetric` (do not forget to include the proper header).

```
    typedef itk::MeanReciprocalSquareDifferenceImageToImageMetric
```

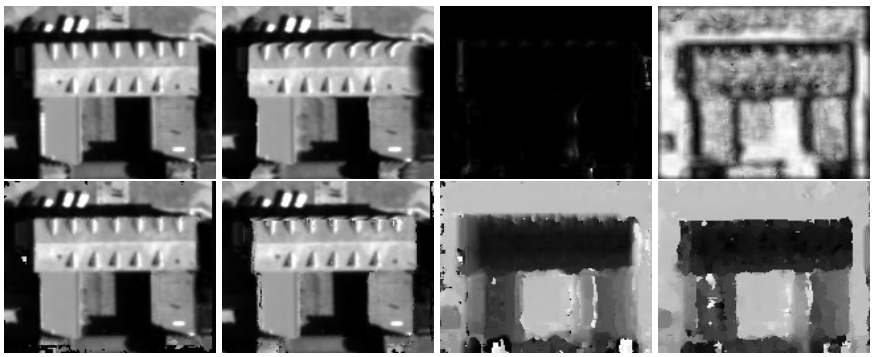


Figure 10.2: From left to right and top to bottom: fixed input image, moving image with a low stereo angle, local correlation field, local mean reciprocal square difference field, resampled image based on correlation, resampled image based on mean reciprocal square difference, estimated epipolar deformation using on correlation, estimated epipolar deformation using mean reciprocal square difference.

```
    <InputImageType, InputImageType> MRSDMetricType;
MRSDMetricType::Pointer mrsdMetric = MRSDMetricType::New();
registrator->SetMetric(mrsdMetric);
```

The `itk::MutualInformationImageToImageMetric` produces low value for poor matches, therefore, the filter has to maximize the metric :

```
registrator->MinimizeOff();
```

The execution of the `otb::FineRegistrationImageFilter` will be triggered by the `Update()` call on the writer at the end of the pipeline. Make sure to use a `otb::ImageFileWriter` if you want to benefit from the streaming features.

Figure 10.2 shows the result of applying the `otb::FineRegistrationImageFilter`.

10.3 Irregular grid disparity map estimation

Taking figure 10.1 as a starting point, we can generalize the approach by letting the user choose:

- the similarity measure;
- the geometric transform to be estimated (see definition 4);

In order to do this, we will use the ITK registration framework locally on a set of nodes. Once the disparity is estimated on a set of nodes, we will use it to generate a deformation field: the dense,

regular vector field which gives the translation to be applied to a pixel of the secondary image to be positioned on its homologous point of the master image.

The source code for this example can be found in the file
`Examples/DisparityMap/SimpleDisparityMapEstimationExample.cxx`.

This example demonstrates the use of the `otb::DisparityMapEstimationMethod`, along with the `otb::NearestPointDisplacementFieldGenerator`. The first filter performs deformation estimation according to a given transform, using embedded ITK registration framework. It takes as input a possibly non regular point set and produces a point set with associated point data representing the deformation.

The second filter generates a deformation field by using nearest neighbor interpolation on the deformation values from the point set. More advanced methods for deformation field interpolation are also available.

The first step toward the use of these filters is to include the proper header files.

```
#include "otbDisparityMapEstimationMethod.h"
#include "itkTranslationTransform.h"
#include "itkNormalizedCorrelationImageToImageMetric.h"
#include "itkWindowedSincInterpolateImageFunction.h"
#include "itkZeroFluxNeumannBoundaryCondition.h"
#include "itkGradientDescentOptimizer.h"
#include "otbBSplinesInterpolateDisplacementFieldGenerator.h"
#include "otbWarpImageFilter.h"
```

Then we must decide what pixel type to use for the image. We choose to do all the computation in floating point precision and rescale the results between 0 and 255 in order to export PNG images.

```
  typedef double        PixelType;
  typedef unsigned char OutputPixelType;
```

The images are defined using the pixel type and the dimension. Please note that the `otb::NearestPointDisplacementFieldGenerator` generates a `otb::VectorImage` to represent the deformation field in both image directions.

```
  typedef otb::Image<PixelType, Dimension>       ImageType;
  typedef otb::Image<OutputPixelType, Dimension> OutputImageType;
```

The next step is to define the transform we have chosen to model the deformation. In this example the deformation is modeled as a `itk::TranslationTransform`.

```
  typedef itk::TranslationTransform<double, Dimension> TransformType;
  typedef TransformType::ParametersType                ParametersType;
```

Then we define the metric we will use to evaluate the local registration between the fixed and the moving image. In this example we choosed the `itk::NormalizedCorrelationImageToImageMetric`.

```
typedef itk::NormalizedCorrelationImageToImageMetric<ImageType,
    ImageType> MetricType;
```

Disparity map estimation implies evaluation of the moving image at non-grid position. Therefore, an interpolator is needed. In this example we choosed the `itk::WindowedSincInterpolateImageFunction`.

```
typedef itk::Function::HammingWindowFunction<3>          WindowFunctionType;
typedef itk::ZeroFluxNeumannBoundaryCondition<ImageType> ConditionType;
typedef itk::WindowedSincInterpolateImageFunction<ImageType, 3,
    WindowFunctionType,
    ConditionType,
    double> InterpolatorType;
```

To perform local registration, an optimizer is needed. In this example we choosed the `itk::GradientDescentOptimizer`.

```
typedef itk::GradientDescentOptimizer OptimizerType;
```

Now we will define the point set to represent the point where to compute local disparity.

```
typedef itk::PointSet<ParametersType, Dimension> PointSetType;
```

Now we define the disparity map estimation filter.

```
typedef otb::DisparityMapEstimationMethod<ImageType,
    ImageType,
    PointSetType> DMEstimationType;
typedef DMEstimationType::SizeType SizeType;
```

The input image reader also has to be defined.

```
typedef otb::ImageFileReader<ImageType> ReaderType;
```

Two readers are instantiated : one for the fixed image, and one for the moving image.

```
ReaderType::Pointer fixedReader = ReaderType::New();
ReaderType::Pointer movingReader = ReaderType::New();

fixedReader->SetFileName(argv[1]);
movingReader->SetFileName(argv[2]);
fixedReader->UpdateOutputInformation();
movingReader->UpdateOutputInformation();
```

We will the create a regular point set where to compute the local disparity.

```
SizeType fixedSize =
  fixedReader->GetOutput()->GetLargestPossibleRegion().GetSize();
unsigned int NumberOfXNodes = (fixedSize[0] - 2 * atoi(argv[7]) - 1)
                              / atoi(argv[5]);
```

```
unsigned int NumberOfYNodes = (fixedSize[1] - 2 * atoi(argv[7]) - 1)
                              / atoi(argv[6]);

ImageType::IndexType firstNodeIndex;
firstNodeIndex[0] = atoi(argv[7]);
firstNodeIndex[1] = atoi(argv[7]);

PointSetType::Pointer nodes = PointSetType::New();
unsigned int          nodeCounter = 0;

for (unsigned int x = 0; x < NumberOfXNodes; x++)
  {
  for (unsigned int y = 0; y < NumberOfYNodes; y++)
    {
    PointType                    p;
    p[0] = firstNodeIndex[0] + x*atoi(argv[5]);
    p[1] = firstNodeIndex[1] + y*atoi(argv[6]);
    nodes->SetPoint(nodeCounter++, p);
    }
  }
```

We build the transform, interpolator, metric and optimizer for the disparity map estimation filter.

```
TransformType::Pointer transform = TransformType::New();

OptimizerType::Pointer optimizer = OptimizerType::New();
optimizer->MinimizeOn();
optimizer->SetLearningRate(atof(argv[9]));
optimizer->SetNumberOfIterations(atoi(argv[10]));

InterpolatorType::Pointer interpolator = InterpolatorType::New();

MetricType::Pointer metric = MetricType::New();
metric->SetSubtractMean(true);
```

We then set up the disparity map estimation filter. This filter will perform a local registration at each point of the given point set using the ITK registration framework. It will produce a point set whose point data reflects the disparity locally around the associated point.

Point data will contains the following data :

1. The final metric value found in the registration process,
2. the deformation value in the first image direction,
3. the deformation value in the second image direction,
4. the final parameters of the transform.

Please note that in the case of a `itk::TranslationTransform`, the deformation values and the transform parameters are the same.

```
DMEstimationType::Pointer dmestimator = DMEstimationType::New();

dmestimator->SetTransform(transform);
dmestimator->SetOptimizer(optimizer);
dmestimator->SetInterpolator(interpolator);
dmestimator->SetMetric(metric);

SizeType windowSize, explorationSize;
explorationSize.Fill(atoi(argv[7]));
windowSize.Fill(atoi(argv[8]));

dmestimator->SetWinSize(windowSize);
dmestimator->SetExploSize(explorationSize);
```

The initial transform parameters can be set via the `SetInitialTransformParameters()` method. In our case, we simply fill the parameter array with null values.

```
DMEstimationType::ParametersType
initialParameters(transform->GetNumberOfParameters());
initialParameters[0] = 0.0;
initialParameters[1] = 0.0;
dmestimator->SetInitialTransformParameters(initialParameters);
```

Now we can set the input for the deformation field estimation filter. Fixed image can be set using the `SetFixedImage()` method, moving image can be set using the `SetMovingImage()`, and input point set can be set using the `SetPointSet()` method.

```
dmestimator->SetFixedImage(fixedReader->GetOutput());
dmestimator->SetMovingImage(movingReader->GetOutput());
dmestimator->SetPointSet(nodes);
```

Once the estimation has been performed by the `otb::DisparityMapEstimationMethod`, one can generate the associated deformation field (that means translation in first and second image direction). It will be represented as a `otb::VectorImage`.

```
typedef otb::VectorImage<PixelType, Dimension> DisplacementFieldType;
```

For the deformation field estimation, we will use the `otb::BSplinesInterpolateDisplacementFieldGenerat` This filter will perform a nearest neighbor interpolation on the deformation values in the point set data.

```
typedef otb::BSplinesInterpolateDisplacementFieldGenerator<PointSetType,
    DisplacementFieldType>
GeneratorType;
```

The disparity map estimation filter is instanciated.

```
GeneratorType::Pointer generator = GeneratorType::New();
```

We must then specify the input point set using the `SetPointSet()` method.

```
generator->SetPointSet(dmestimator->GetOutput());
```

One must also specify the origin, size and spacing of the output deformation field.

```
generator->SetOutputOrigin(fixedReader->GetOutput()->GetOrigin());
generator->SetOutputSpacing(fixedReader->GetOutput()->GetSpacing());
generator->SetOutputSize(fixedReader->GetOutput()
                         ->GetLargestPossibleRegion().GetSize());
```

The local registration process can lead to wrong deformation values and transform parameters. To Select only points in point set for which the registration process was succesful, one can set a threshold on the final metric value : points for which the absolute final metric value is below this threshold will be discarded. This threshold can be set with the `SetMetricThreshold()` method.

```
generator->SetMetricThreshold(atof(argv[11]));
```

The following classes provide similar functionality:

- `otb::NNearestPointsLinearInterpolateDisplacementFieldGenerator`
- `otb::BSplinesInterpolateDisplacementFieldGenerator`
- `otb::NearestTransformDisplacementFieldGenerator`
- `otb::NNearestTransformsLinearInterpolateDisplacementFieldGenerator`
- `otb::BSplinesInterpolateTransformDisplacementFieldGenerator`

Now we can warp our fixed image according to the estimated deformation field. This will be performed by the `itk::WarpImageFilter`. First, we define this filter.

```
typedef otb::WarpImageFilter<ImageType, ImageType,
    DisplacementFieldType> ImageWarperType;
```

Then we instantiate it.

```
ImageWarperType::Pointer warper = ImageWarperType::New();
```

We set the input image to warp using the `SetInput()` method, and the deformation field using the `SetDisplacementField()` method.

```
warper->SetInput(movingReader->GetOutput());
warper->SetDisplacementField(generator->GetOutput());
warper->SetOutputOrigin(fixedReader->GetOutput()->GetOrigin());
warper->SetOutputSpacing(fixedReader->GetOutput()->GetSpacing());
```

In order to write the result to a PNG file, we will rescale it on a proper range.

```
typedef itk::RescaleIntensityImageFilter<ImageType,
    OutputImageType> RescalerType;

RescalerType::Pointer outputRescaler = RescalerType::New();
outputRescaler->SetInput(warper->GetOutput());
outputRescaler->SetOutputMaximum(255);
outputRescaler->SetOutputMinimum(0);
```

We can now write the image to a file. The filters are executed by invoking the `Update()` method.

```
typedef otb::ImageFileWriter<OutputImageType> WriterType;

WriterType::Pointer outputWriter = WriterType::New();
outputWriter->SetInput(outputRescaler->GetOutput());
outputWriter->SetFileName(argv[4]);
outputWriter->Update();
```

We also want to write the deformation field along the first direction to a file. To achieve this we will use the `otb::MultiToMonoChannelExtractROI` filter.

```
typedef otb::MultiToMonoChannelExtractROI<PixelType,
    PixelType>
ChannelExtractionFilterType;

ChannelExtractionFilterType::Pointer channelExtractor
  = ChannelExtractionFilterType::New();

channelExtractor->SetInput(generator->GetOutput());
channelExtractor->SetChannel(1);

RescalerType::Pointer fieldRescaler = RescalerType::New();
fieldRescaler->SetInput(channelExtractor->GetOutput());
fieldRescaler->SetOutputMaximum(255);
fieldRescaler->SetOutputMinimum(0);

WriterType::Pointer fieldWriter = WriterType::New();
fieldWriter->SetInput(fieldRescaler->GetOutput());
fieldWriter->SetFileName(argv[3]);
fieldWriter->Update();
```

Figure 10.3 shows the result of applying disparity map estimation on a stereo pair using a regular point set, followed by deformation field estimation using Splines and fixed image resampling.

10.4 Stereo reconstruction

The source code for this example can be found in the file
`Examples/DisparityMap/StereoReconstructionExample.cxx`.

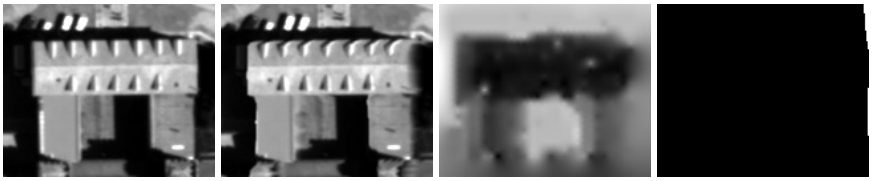


Figure 10.3: From left to right and top to bottom: fixed input image, moving image with a sinusoid deformation, estimated deformation field in the horizontal direction, resampled moving image.

This example demonstrates the use of the stereo reconstruction chain from an image pair. The images are assumed to come from the same sensor but with different positions. The approach presented here has the following steps:

- Epipolar resampling of the image pair
- Dense disparity map estimation
- Projection of the disparities on an existing Digital Elevation Model (DEM)

It is important to note that this method requires the sensor models with a pose estimate for each image.

```
#include "otbStereorectificationDisplacementFieldSource.h"
#include "otbStreamingWarpImageFilter.h"
#include "otbPixelWiseBlockMatchingImageFilter.h"
#include "otbBandMathImageFilter.h"
#include "otbSubPixelDisparityImageFilter.h"
#include "otbDisparityMapMedianFilter.h"
#include "otbDisparityMapToDEMFilter.h"

#include "otbImage.h"
#include "otbVectorImage.h"
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
#include "otbBCOInterpolateImageFunction.h"
#include "itkVectorCastImageFilter.h"
#include "otbImageList.h"
#include "otbImageListToVectorImageFilter.h"
#include "itkRescaleIntensityImageFilter.h"
#include "otbDEMHandler.h"
```

This example demonstrates the use of the following filters :

- `otb::StereorectificationDisplacementFieldSource`
- `otb::StreamingWarpImageFilter`
- `otb::PixelWiseBlockMatchingImageFilter`

- otb::otbSubPixelDisparityImageFilter
- otb::otbDisparityMapMedianFilter
- otb::DisparityMapToDEMFilter

```
typedef otb::StereorectificationDisplacementFieldSource
  <FloatImageType,FloatVectorImageType>     DisplacementFieldSourceType;

typedef itk::Vector<double,2>               DisplacementType;
typedef otb::Image<DisplacementType>         DisplacementFieldType;

typedef itk::VectorCastImageFilter
  <FloatVectorImageType,
   DisplacementFieldType>                    DisplacementFieldCastFilterType;

typedef otb::StreamingWarpImageFilter
  <FloatImageType,
   FloatImageType,
   DisplacementFieldType>                    WarpFilterType;

typedef otb::BCOInterpolateImageFunction
  <FloatImageType>                          BCOInterpolationType;

typedef otb::Functor::NCCBlockMatching
  <FloatImageType,FloatImageType>           NCCBlockMatchingFunctorType;

typedef otb::PixelWiseBlockMatchingImageFilter
  <FloatImageType,
   FloatImageType,
   FloatImageType,
   FloatImageType,
   NCCBlockMatchingFunctorType>             NCCBlockMatchingFilterType;

typedef otb::BandMathImageFilter
  <FloatImageType>                          BandMathFilterType;

typedef otb::SubPixelDisparityImageFilter
  <FloatImageType,
   FloatImageType,
   FloatImageType,
   FloatImageType,
   NCCBlockMatchingFunctorType>             NCCSubPixelDisparityFilterType;

typedef otb::DisparityMapMedianFilter
  <FloatImageType,
   FloatImageType,
   FloatImageType>                          MedianFilterType;

typedef otb::DisparityMapToDEMFilter
  <FloatImageType,
   FloatImageType,
   FloatImageType,
   FloatVectorImageType,
```

```
    FloatImageType>                              DisparityToElevationFilterType;
```

The image pair is supposed to be in sensor geometry. From two images covering nearly the same area, one can estimate a common epipolar geometry. In this geometry, an altitude variation corresponds to an horizontal shift between the two images. The filter `otb::StereorectificationDisplacementFieldSource` computes the deformation grids for each image.

These grids are sampled in epipolar geometry. They have two bands, containing the position offset (in physical space units) between the current epipolar point and the corresponding sensor point in horizontal and vertical direction. They can be computed at a lower resolution than sensor resolution. The application `StereoRectificationGridGenerator` also provides a simple tool to generate the epipolar grids for your image pair.

```
DisplacementFieldSourceType::Pointer m_DisplacementFieldSource = DisplacementFieldSourceType::New();
m_DisplacementFieldSource->SetLeftImage(leftReader->GetOutput());
m_DisplacementFieldSource->SetRightImage(rightReader->GetOutput());
m_DisplacementFieldSource->SetGridStep(4);
m_DisplacementFieldSource->SetScale(1.0);
//m_DisplacementFieldSource->SetAverageElevation(avgElevation);

m_DisplacementFieldSource->Update();
```

Then, the sensor images can be resampled in epipolar geometry, using the `otb::StreamingWarpImageFilter`. The application `GridBasedImageResampling` also gives an easy access to this filter. The user can choose the epipolar region to resample, as well as the resampling step and the interpolator.

Note that the epipolar image size can be retrieved from the stereo rectification grid filter.

```
FloatImageType::SpacingType epipolarSpacing;
epipolarSpacing[0] = 1.0;
epipolarSpacing[1] = 1.0;

FloatImageType::SizeType epipolarSize;
epipolarSize = m_DisplacementFieldSource->GetRectifiedImageSize();

FloatImageType::PointType epipolarOrigin;
epipolarOrigin[0] = 0.0;
epipolarOrigin[1] = 0.0;

FloatImageType::PixelType defaultValue = 0;
```

The deformation grids are casted into deformation fields, then the left and right sensor images are resampled.

```
DisplacementFieldCastFilterType::Pointer m_LeftDisplacementFieldCaster = DisplacementFieldCastFilter
m_LeftDisplacementFieldCaster->SetInput(m_DisplacementFieldSource->GetLeftDisplacementFieldOutput())
m_LeftDisplacementFieldCaster->GetOutput()->UpdateOutputInformation();

BCOInterpolationType::Pointer leftInterpolator = BCOInterpolationType::New();
```

```
leftInterpolator->SetRadius(2);

WarpFilterType::Pointer m_LeftWarpImageFilter = WarpFilterType::New();
m_LeftWarpImageFilter->SetInput(leftReader->GetOutput());
m_LeftWarpImageFilter->SetDisplacementField(m_LeftDisplacementFieldCaster->GetOutput());
m_LeftWarpImageFilter->SetInterpolator(leftInterpolator);
m_LeftWarpImageFilter->SetOutputSize(epipolarSize);
m_LeftWarpImageFilter->SetOutputSpacing(epipolarSpacing);
m_LeftWarpImageFilter->SetOutputOrigin(epipolarOrigin);
m_LeftWarpImageFilter->SetEdgePaddingValue(defaultValue);

DisplacementFieldCastFilterType::Pointer m_RightDisplacementFieldCaster = DisplacementFieldC
m_RightDisplacementFieldCaster->SetInput(m_DisplacementFieldSource->GetRightDisplacementFiel
m_RightDisplacementFieldCaster->GetOutput()->UpdateOutputInformation();

BCOInterpolationType::Pointer rightInterpolator = BCOInterpolationType::New();
rightInterpolator->SetRadius(2);

WarpFilterType::Pointer m_RightWarpImageFilter = WarpFilterType::New();
m_RightWarpImageFilter->SetInput(rightReader->GetOutput());
m_RightWarpImageFilter->SetDisplacementField(m_RightDisplacementFieldCaster->GetOutput());
m_RightWarpImageFilter->SetInterpolator(rightInterpolator);
m_RightWarpImageFilter->SetOutputSize(epipolarSize);
m_RightWarpImageFilter->SetOutputSpacing(epipolarSpacing);
m_RightWarpImageFilter->SetOutputOrigin(epipolarOrigin);
m_RightWarpImageFilter->SetEdgePaddingValue(defaultValue);
```

Since the resampling produces black regions around the image, it is useless to estimate disparities on these *no-data* regions. We use a `otb::BandMathImageFilter` to produce a mask on left and right epipolar images.

```
BandMathFilterType::Pointer m_LBandMathFilter = BandMathFilterType::New();
m_LBandMathFilter->SetNthInput(0,m_LeftWarpImageFilter->GetOutput(),"inleft");
#ifdef OTB_MUPARSER_HAS_CXX_LOGICAL_OPERATORS
std::string leftExpr = "inleft != 0 ? 255 : 0";
#else
std::string leftExpr = "if(inleft != 0,255,0)";
#endif

m_LBandMathFilter->SetExpression(leftExpr);

BandMathFilterType::Pointer m_RBandMathFilter = BandMathFilterType::New();
m_RBandMathFilter->SetNthInput(0,m_RightWarpImageFilter->GetOutput(),"inright");

#ifdef OTB_MUPARSER_HAS_CXX_LOGICAL_OPERATORS
std::string rightExpr = "inright != 0 ? 255 : 0";
#else
std::string rightExpr = "if(inright != 0,255,0)";
#endif

m_RBandMathFilter->SetExpression(rightExpr);
```

Once the two sensor images have been resampled in epipolar geometry, the disparity map can be

computed. The approach presented here is a 2D matching based on a pixel-wise metric optimization. This approach doesn't give the best results compared to global optimization methods, but it is suitable for streaming and threading on large images.

The major filter used for this step is `otb::PixelWiseBlockMatchingImageFilter`. The metric is computed on a window centered around the tested epipolar position. It performs a pixel-to-pixel matching between the two epipolar images. The output disparities are given as index offset from left to right position. The following features are available in this filter:

- Available metrics : SSD, NCC and L^p pseudo norm (computed on a square window)
- Rectangular disparity exploration area.
- Input masks for left and right images (optional).
- Output metric values (optional).
- Possibility to use input disparity estimate (as a uniform value or a full map) and an exploration radius around these values to reduce the size of the exploration area (optional).

```
NCCBlockMatchingFilterType::Pointer m_NCCBlockMatcher = NCCBlockMatchingFilterType::New();
m_NCCBlockMatcher->SetLeftInput(m_LeftWarpImageFilter->GetOutput());
m_NCCBlockMatcher->SetRightInput(m_RightWarpImageFilter->GetOutput());
m_NCCBlockMatcher->SetRadius(3);
m_NCCBlockMatcher->SetMinimumHorizontalDisparity(-24);
m_NCCBlockMatcher->SetMaximumHorizontalDisparity(0);
m_NCCBlockMatcher->SetMinimumVerticalDisparity(0);
m_NCCBlockMatcher->SetMaximumVerticalDisparity(0);
m_NCCBlockMatcher->MinimizeOff();
m_NCCBlockMatcher->SetLeftMaskInput(m_LBandMathFilter->GetOutput());
m_NCCBlockMatcher->SetRightMaskInput(m_RBandMathFilter->GetOutput());
```

Some other filters have been added to enhance these *pixel-to-pixel* disparities. The filter `otb::SubPixelDisparityImageFilter` can estimate the disparities with sub-pixel precision. Several interpolation methods can be used : parabolic fit, triangular fit, and dichotomy search.

```
NCCSubPixelDisparityFilterType::Pointer m_NCCSubPixFilter = NCCSubPixelDisparityFilterType::New();
m_NCCSubPixFilter->SetInputsFromBlockMatchingFilter(m_NCCBlockMatcher);
m_NCCSubPixFilter->SetRefineMethod(NCCSubPixelDisparityFilterType::DICHOTOMY);
```

The filter `otb::DisparityMapMedianFilter` can be used to remove outliers. It has two parameters:

- The radius of the local neighborhood to compute the median
- An incoherence threshold to reject disparities whose distance from the local median is superior to the threshold.

```
MedianFilterType::Pointer m_HMedianFilter = MedianFilterType::New();
m_HMedianFilter->SetInput(m_NCCSubPixFilter->GetHorizontalDisparityOutput());
m_HMedianFilter->SetRadius(2);
m_HMedianFilter->SetIncoherenceThreshold(2.0);
m_HMedianFilter->SetMaskInput(m_LBandMathFilter->GetOutput());

MedianFilterType::Pointer m_VMedianFilter = MedianFilterType::New();
m_VMedianFilter->SetInput(m_NCCSubPixFilter->GetVerticalDisparityOutput());
m_VMedianFilter->SetRadius(2);
m_VMedianFilter->SetIncoherenceThreshold(2.0);
m_VMedianFilter->SetMaskInput(m_LBandMathFilter->GetOutput());
```

The application `PixelWiseBlockMatching` contains all these filters and provides a single interface to compute your disparity maps.

The disparity map obtained with the previous step usually gives a good idea of the altitude profile. However, it is more useful to study altitude with a DEM (Digital Elevation Model) representation.

The filter `otb::DisparityMapToDEMFilter` performs this last step. The behavior of this filter is to :

- Compute the DEM extent from the left sensor image envelope (spacing is set by the user)
- Compute the left and right rays corresponding to each valid disparity
- Compute the intersection with the *mid-point* method
- If the 3D point falls inside a DEM cell and has a greater elevation than the current height, the cell height is updated

The rule of keeping the highest elevation makes sense for buildings seen from the side because the roof edges elevation has to be kept. However this rule is not suited for noisy disparities.

The application `DisparityMapToElevationMap` also gives an example of use.

```
DisparityToElevationFilterType::Pointer m_DispToElev = DisparityToElevationFilterType::New()
m_DispToElev->SetHorizontalDisparityMapInput(m_HMedianFilter->GetOutput());
m_DispToElev->SetVerticalDisparityMapInput(m_VMedianFilter->GetOutput());
m_DispToElev->SetLeftInput(leftReader->GetOutput());
m_DispToElev->SetRightInput(rightReader->GetOutput());
m_DispToElev->SetLeftEpipolarGridInput(m_DisplacementFieldSource->GetLeftDisplacementFieldOu
m_DispToElev->SetRightEpipolarGridInput(m_DisplacementFieldSource->GetRightDisplacementField
m_DispToElev->SetElevationMin(avgElevation-10.0);
m_DispToElev->SetElevationMax(avgElevation+80.0);
m_DispToElev->SetDEMGridStep(2.5);
m_DispToElev->SetDisparityMaskInput(m_LBandMathFilter->GetOutput());
//m_DispToElev->SetAverageElevation(avgElevation);

WriterType::Pointer m_DEMWriter = WriterType::New();
m_DEMWriter->SetInput(m_DispToElev->GetOutput());
m_DEMWriter->SetFileName(argv[3]);
```

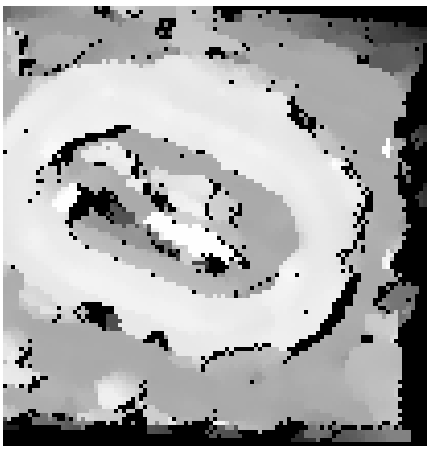


Figure 10.4: DEM image estimated from the disparity.

```
m_DEMWriter->Update();

RescalerType::Pointer fieldRescaler = RescalerType::New();
fieldRescaler->SetInput(m_DispToElev->GetOutput());
fieldRescaler->SetOutputMaximum(255);
fieldRescaler->SetOutputMinimum(0);

OutputWriterType::Pointer fieldWriter = OutputWriterType::New();
fieldWriter->SetInput(fieldRescaler->GetOutput());
fieldWriter->SetFileName(argv[4]);
fieldWriter->Update();
```

Figure 10.4 shows the result of applying terrain reconstruction based using pixel-wise block matching, sub-pixel interpolation and DEM estimation using a pair of Pleiades images over the *Stadium* in Toulouse, France.

CHAPTER

ELEVEN

ORTHORECTIFICATION AND MAP PROJECTION

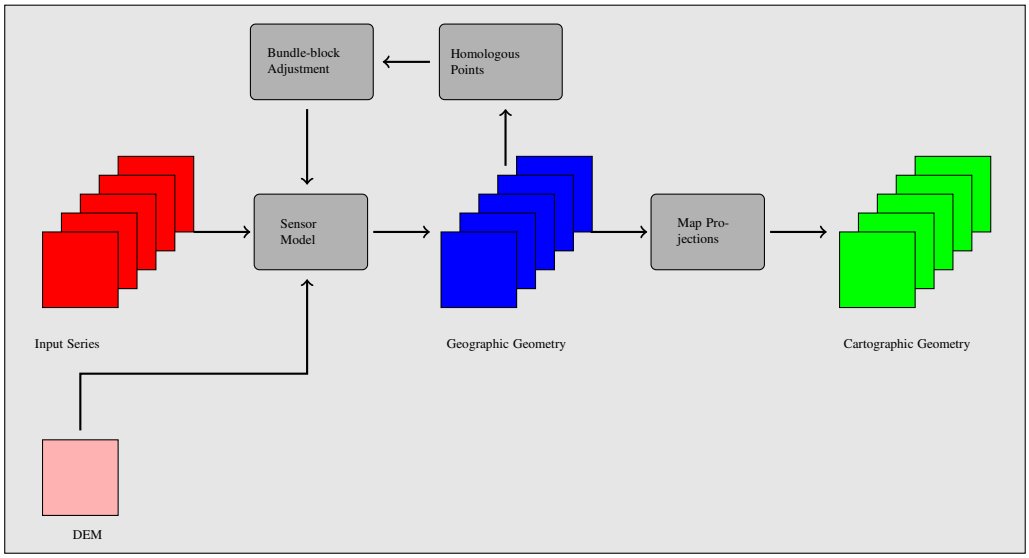


Figure 11.1: Image Ortho-registration Procedure.

This chapter introduces the functionnalities available in OTB for image ortho-registration. We define ortho-registration as the procedure allowing to transform an image in sensor geometry to a geographic or cartographic projection.

Figure 11.1 shows a synoptic view of the different steps involved in a classical ortho-registration processing chain able to deal with image series. These steps are the following:

- Sensor modelling: the geometric sensor model allows to convert image coordinates (line, column) into geographic coordinates (latitude, longitude); a rigorous modelling needs a digital elevation model (DEM) in order to take into account the terrain topography.
- Bundle-block adjustment: in the case of image series, the geometric models and their parameters can be refined by using homologous points between the images. This is an optional step and not currently implemented in OTB.
- Map projection: this step allows to go from geographic coordinates to some specific cartographic projection as Lambert, Mercator or UTM.

11.1 Sensor Models

A sensor model is a set of equations giving the relationship between image pixel (l,c) coordinates and ground (X,Y) coordinates for every pixel in the image. Typically, the ground coordinates are given in a geographic projection (latitude, longitude). The sensor model can be expressed either from image to ground – forward model – or from ground to image – inverse model. This can be written as follows:

$$\begin{array}{c} \textit{Forward} \\ X = f_x(l,c,h,\vec{\theta}) \quad Y = f_y(l,c,h,\vec{\theta}) \end{array}$$

$$\begin{array}{c} \textit{Inverse} \\ l = g_l(X,Y,h,\vec{\theta}) \quad c = g_c(X,Y,h,\vec{\theta}) \end{array}$$

Where $\vec{\theta}$ is the set of parameters which describe the sensor and the acquisition geometry (platform altitude, viewing angle, focal length for optical sensors, doppler centroid for SAR images, etc.).

In OTB, sensor models are implemented as `itk::Transforms` (see section 9.6 for details), which is the appropriate way to express coordinate changes. The base class for sensor models is `otb::SensorModelBase` from which the classes `otb::InverseSensorModel` and `otb::ForwardSensorModel` inherit.

As one may note from the model equations, the height of the ground, h, must be known. Usually, it means that a Digital Elevation Model, DEM, will be used.

11.1.1 Types of Sensor Models

There exists two main types of sensor models. On one hand, we have the so-called *physical models*, which are rigorous, complex, eventually highly non-linear equations of the sensor geometry. As

such, they are difficult to inverse (obtain the inverse model from the forward one and vice-versa). They have the significant advantage of having parameters with physical meaning (angles, distances, etc.). They are specific of each sensor, which means that a library of models is required in the software. A library which has to be updated every time a new sensor is available.

On the other hand, we have general analytical models, which approximate the physical models. These models can take the form of polynomials or ratios of polynomials, the so-called rational polynomial functions or Rational Polynomial Coefficients, RPC, also known as *Rapid Positioning Capability*. Since they are approximations, they are less accurate than the physical models. However, the achieved accuracy is usually high: in the case of Pléiades, RPC models have errors lower than 0.02 pixels with respect to the physical model. Since these models have a standard form they are easier to use and implement. However, they have the drawback of having parameters (coefficients, actually) without physical meaning.

OTB, through the use of the OSSIM library – `http://www.ossim.org` – offers models for most of current sensors either through a physical or an analytical approach. This is transparent for the user, since the geometrical model for a given image is instantiated using the information stored in its meta-data.

11.1.2 Using Sensor Models

The transformation of an image in sensor geometry to geographic geometry can be done using the following steps.

1. Read image meta-data and instantiate the model with the given parameters.
2. Define the ROI in ground coordinates (this is your output pixel array)
3. Iterate through the pixels of coordinates (X,Y):
   (a) Get h from the DEM
   (b) Compute $(c,l) = G(X,Y,h,\vec{\theta})$
   (c) Interpolate pixel values if (c,l) are not grid coordinates.

Actually, in OTB, you don't have to manually instantiate the sensor model which is appropriate to your image. That is, you don't have to manually choose a SPOT5 or a Quickbird sensor model. This task is automatically performed by the `otb::ImageFileReader` class in a similar way as the image format recognition is done. The appropriate sensor model will then be included in the image meta-data, so you can access it when needed.

The source code for this example can be found in the file
`Examples/Projections/SensorModelExample.cxx`.

This example illustrates how to use the sensor model read from image meta-data in order to perform ortho-rectification. This is a very basic, step-by-step example, so you understand the different components involved in the process. When performing real ortho-rectifications, you can use the example presented in section 11.3.

We will start by including the header file for the inverse sensor model.

```
#include "otbInverseSensorModel.h"
```

As explained before, the first thing to do is to create the sensor model in order to transform the ground coordinates in sensor geometry coordinates. The geoetric model will automatically be created by the image file reader. So we begin by declaring the types for the input image and the image reader.

```
typedef otb::Image<unsigned int, 2>     ImageType;
typedef otb::ImageFileReader<ImageType> ReaderType;

ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(argv[1]);

ImageType::Pointer inputImage = reader->GetOutput();
```

We have just instantiated the reader and set the file name, but the image data and meta-data has not yet been accessed by it. Since we need the creation of the sensor model and all the image information (size, spacing, etc.), but we do not want to read the pixel data – it could be huge – we just ask the reader to generate the output information needed.

```
reader->GenerateOutputInformation();

std::cout << "Original input imagine spacing: " <<
reader->GetOutput()->GetSpacing() << std::endl;
```

We can now instantiate the sensor model – an inverse one, since we want to convert ground coordinates to sensor geometry. Note that the choice of the specific model (SPOT5, Ikonos, etc.) is done by the reader and we only need to instantiate a generic model.

```
typedef otb::InverseSensorModel<double> ModelType;
ModelType::Pointer model = ModelType::New();
```

The model is parameterized by passing to it the *keyword list* containing the needed information.

```
model->SetImageGeometry(reader->GetOutput()->GetImageKeywordlist());
```

Since we can not be sure that the image we read actually has sensor model information, we must check for the model validity.

```
if (model->IsValidSensorModel() == false)
  {
  std::cerr << "Unable to create a model" << std::endl;
  return 1;
  }
```

The types for the input and output coordinate points can be now declared. The same is done for the index types.

```
ModelType::OutputPointType inputPoint;
typedef itk::Point <double, 2> PointType;
PointType outputPoint;

ImageType::IndexType currentIndex;
ImageType::IndexType currentIndexBis;
ImageType::IndexType pixelIndexBis;
```

We will now create the output image over which we will iterate in order to transform ground coordinates to sensor coordinates and get the corresponding pixel values.

```
ImageType::Pointer outputImage = ImageType::New();

ImageType::PixelType pixelValue;

ImageType::IndexType start;
start[0] = 0;
start[1] = 0;

ImageType::SizeType size;
size[0] = atoi(argv[5]);
size[1] = atoi(argv[6]);
```

The spacing in y direction is negative since origin is the upper left corner.

```
ImageType::SpacingType spacing;
spacing[0] = 0.00001;
spacing[1] = -0.00001;

ImageType::PointType origin;
origin[0] = strtod(argv[3], NULL);          //longitude
origin[1] = strtod(argv[4], NULL);          //latitude

ImageType::RegionType region;

region.SetSize(size);
region.SetIndex(start);

outputImage->SetOrigin(origin);
outputImage->SetRegions(region);
outputImage->SetSpacing(spacing);
outputImage->Allocate();
```

We will now instantiate an extractor filter in order to get input regions by manual tiling.

```
typedef itk::ExtractImageFilter<ImageType, ImageType> ExtractType;
ExtractType::Pointer extract = ExtractType::New();
```

Since the transformed coordinates in sensor geometry may not be integer ones, we will need an interpolator to retrieve the pixel values (note that this assumes that the input image was correctly sampled by the acquisition system).

```
typedef itk::LinearInterpolateImageFunction<ImageType, double>
InterpolatorType;
InterpolatorType::Pointer interpolator = InterpolatorType::New();
```

We proceed now to create the image writer. We will also use a writer plugged to the output of the extractor filter which will write the temporary extracted regions. This is just for monitoring the process.

```
typedef otb::Image<unsigned char, 2>        CharImageType;
typedef otb::ImageFileWriter<CharImageType> CharWriterType;
typedef otb::ImageFileWriter<ImageType>     WriterType;
WriterType::Pointer     extractorWriter = WriterType::New();
CharWriterType::Pointer writer = CharWriterType::New();
extractorWriter->SetFileName("image_temp.jpeg");
extractorWriter->SetInput(extract->GetOutput());
```

Since the output pixel type and the input pixel type are different, we will need to rescale the intensity values before writing them to a file.

```
typedef itk::RescaleIntensityImageFilter
<ImageType, CharImageType> RescalerType;
RescalerType::Pointer rescaler = RescalerType::New();
rescaler->SetOutputMinimum(10);
rescaler->SetOutputMaximum(255);
```

The tricky part starts here. Note that this example is only intended for educationnal purposes and that you do not need to proceed as this. See the example in section 11.3 in order to code ortho-rectification chains in a very simple way.

You want to go on? OK. You have been warned.

We will start by declaring an image region iterator and some convenience variables.

```
typedef itk::ImageRegionIteratorWithIndex<ImageType> IteratorType;

unsigned int NumberOfStreamDivisions;
if (atoi(argv[7]) == 0)
  {
  NumberOfStreamDivisions = 10;
  }
else
  {
  NumberOfStreamDivisions = atoi(argv[7]);
  }

unsigned int          count = 0;
```

```
unsigned int           It, j, k;
int                    max_x, max_y, min_x, min_y;
ImageType::IndexType   iterationRegionStart;
ImageType::SizeType    iteratorRegionSize;
ImageType::RegionType  iteratorRegion;
```

The loop starts here.

```
for (count = 0; count < NumberOfStreamDivisions; count++)
  {
  iteratorRegionSize[0] = atoi(argv[5]);
  if (count == NumberOfStreamDivisions - 1)
    {
    iteratorRegionSize[1] = (atoi(argv[6])) - ((int) (((atoi(argv[6])) /
                                                       NumberOfStreamDivisions)
                                                      + 0.5)) * (count);
    iterationRegionStart[1] = (atoi(argv[5])) - (iteratorRegionSize[1]);
    }
  else
    {
    iteratorRegionSize[1] = (int) (((atoi(argv[6])) /
                                    NumberOfStreamDivisions) + 0.5);
    iterationRegionStart[1] = count * iteratorRegionSize[1];
    }
  iterationRegionStart[0] = 0;
  iteratorRegion.SetSize(iteratorRegionSize);
  iteratorRegion.SetIndex(iterationRegionStart);
```

We create an array for storing the pixel indexes.

```
  unsigned int pixelIndexArrayDimension = iteratorRegionSize[0] *
                                          iteratorRegionSize[1] * 2;
  int *pixelIndexArray = new int[pixelIndexArrayDimension];
  int *currentIndexArray = new int[pixelIndexArrayDimension];
```

We create an iterator for each piece of the image, and we iterate over them.

```
  IteratorType outputIt(outputImage, iteratorRegion);

  It = 0;
  for (outputIt.GoToBegin(); !outputIt.IsAtEnd(); ++outputIt)
    {
```

We get the current index.

```
    currentIndex = outputIt.GetIndex();
```

We transform the index to physical coordinates.

```
    outputImage->TransformIndexToPhysicalPoint(currentIndex, outputPoint);
```

We use the sensor model to get the pixel coordinates in the input image and we transform this coodinates to an index. Then we store the index in the array. Note that the `TransformPoint()` method of the model has been overloaded so that it can be used with a 3D point when the height of the ground point is known (DEM availability).

```
    inputPoint = model->TransformPoint(outputPoint);

    pixelIndexArray[It] = static_cast<int>(inputPoint[0]);
    pixelIndexArray[It + 1] = static_cast<int>(inputPoint[1]);

    currentIndexArray[It] = static_cast<int>(currentIndex[0]);
    currentIndexArray[It + 1] = static_cast<int>(currentIndex[1]);

    It = It + 2;
    }
```

At this point, we have stored all the indexes we need for the piece of image we are processing. We can now compute the bounds of the area in the input image we need to extract.

```
  max_x = pixelIndexArray[0];
  min_x = pixelIndexArray[0];
  max_y = pixelIndexArray[1];
  min_y = pixelIndexArray[1];

  for (j = 0; j < It; ++j)
    {
    if (j % 2 == 0 && pixelIndexArray[j] > max_x)
      {
      max_x = pixelIndexArray[j];
      }
    if (j % 2 == 0 && pixelIndexArray[j] < min_x)
      {
      min_x = pixelIndexArray[j];
      }
    if (j % 2 != 0 && pixelIndexArray[j] > max_y)
      {
      max_y = pixelIndexArray[j];
      }
    if (j % 2 != 0 && pixelIndexArray[j] < min_y)
      {
      min_y = pixelIndexArray[j];
      }
    }
```

We can now set the parameters for the extractor using a little bit of margin in order to cope with irregular geometric distortions which could be due to topography, for instance.

```
  ImageType::RegionType extractRegion;

  ImageType::IndexType extractStart;

  if (min_x < 10 && min_y < 10)
    {
```

```
    extractStart[0] = 0;
    extractStart[1] = 0;
    }
  else
    {
    extractStart[0] = min_x - 10;
    extractStart[1] = min_y - 10;
    }

  ImageType::SizeType extractSize;

  extractSize[0] = (max_x - min_x) + 20;
  extractSize[1] = (max_y - min_y) + 20;
  extractRegion.SetSize(extractSize);
  extractRegion.SetIndex(extractStart);

  extract->SetExtractionRegion(extractRegion);
  extract->SetInput(reader->GetOutput());
  extractorWriter->Update();
```

We give the input image to the interpolator and we loop through the index array in order to get the corresponding pixel values. Note that for every point we check whether it is inside the extracted region.

```
  interpolator->SetInputImage(extract->GetOutput());

  for (k = 0; k < It / 2; ++k)
    {
    pixelIndexBis[0] = pixelIndexArray[2 * k];
    pixelIndexBis[1] = pixelIndexArray[2 * k + 1];
    currentIndexBis[0] = currentIndexArray[2 * k];
    currentIndexBis[1] = currentIndexArray[2 * k + 1];

    if (interpolator->IsInsideBuffer(pixelIndexBis))
      {
      pixelValue = int(interpolator->EvaluateAtIndex(pixelIndexBis));
      }
    else
      {
      pixelValue = 0;
      }

    outputImage->SetPixel(currentIndexBis, pixelValue);
    }
  delete pixelIndexArray;
  delete currentIndexArray;

  }
```

So we are done. We can now write the output image to a file after performing the intensity rescaling.

```
writer->SetFileName(argv[2]);
```

```
rescaler->SetInput(outputImage);

writer->SetInput(rescaler->GetOutput());
writer->Update();
```

11.1.3 Evaluating Sensor Model

If no appropriate sensor model is available in the image meta-data, OTB offers the possibility to estimate a sensor model from the image.

The source code for this example can be found in the file
`Examples/Projections/EstimateRPCSensorModelExample.cxx`.

The following example illustrates the application of estimation of a sensor model to an image (limited to a RPC sensor model for now).

The `otb::GCPsToRPCSensorModelImageFilter` estimates a RPC sensor model from a list of user defined GCPs. Internally, it uses an ossimRpcSolver, which performs the estimation using the well known least-square method.

Let's look at the minimal code required to use this algorithm. First, the following header defining the `otb::GCPsToRPCSensorModelImageFilter` class must be included.

```
#include <ios>
#include "otbImage.h"
#include "otbImageFileReader.h"
#include "otbGCPsToRPCSensorModelImageFilter.h"
```

We declare the image type based on a particular pixel type and dimension. In this case the `float` type is used for the pixels.

```
typedef otb::Image<float, 2>            ImageType;
typedef otb::ImageFileReader<ImageType> ReaderType;

typedef otb::GCPsToRPCSensorModelImageFilter<ImageType>
GCPsToSensorModelFilterType;

typedef GCPsToSensorModelFilterType::Point2DType Point2DType;
typedef GCPsToSensorModelFilterType::Point3DType Point3DType;
```

The `otb::GCPsToRPCSensorModelImageFilter` is instantiated.

```
GCPsToSensorModelFilterType::Pointer rpcEstimator =
  GCPsToSensorModelFilterType::New();
rpcEstimator->SetInput(reader->GetOutput());
```

We retrieve the command line parameters and put them in the correct variables. Firstly, We determine the number of GCPs set from the command line parameters and they are stored in:

- otb::Point3DType : Store the sensor point (3D ground point)
- otb::Point2DType : Pixel assotiated in the image (2D physical coordinates)

  Here we do not use DEM or MeanElevation. It is also possible to give a 2D ground point and use the DEM or MeanElevation to get the corresponding elevation.

```
for (unsigned int gcpId = 0; gcpId < nbGCPs; ++gcpId)
  {
  Point2DType sensorPoint;
  sensorPoint[0] = atof(argv[3 + gcpId * 5]);
  sensorPoint[1] = atof(argv[4 + gcpId * 5]);

  Point3DType geoPoint;
  geoPoint[0] = atof(argv[5 + 5 * gcpId]);
  geoPoint[1] = atof(argv[6 + 5 * gcpId]);
  geoPoint[2] = atof(argv[7 + 5 * gcpId]);

  std::cout << "Adding GCP sensor: " << sensorPoint << " <-> geo: " <<
  geoPoint << std::endl;

  rpcEstimator->AddGCP(sensorPoint, geoPoint);
  }
```

Note that the otb::GCPsToRPCSensorModelImageFilter needs at least 16 GCPs to estimate a proper RPC sensor model, although no warning will be reported to the user if the number of GCPs is lower than 16. Actual estimation of the sensor model takes place in the GenerateOutputInformation() method.

```
rpcEstimator->GetOutput()->UpdateOutputInformation();
```

The result of the RPC model estimation and the residual ground error is then save in a txt file. Note that This filter does not modify the image buffer, but only the metadata.

```
std::ofstream ofs;
ofs.open(outfname);

// Set floatfield to format properly
ofs.setf(std::ios::fixed, std::ios::floatfield);
ofs.precision(10);

ofs << (ImageType::Pointer) rpcEstimator->GetOutput() << std::endl;
ofs << "Residual ground error: " << rpcEstimator->GetRMSGroundError() <<
std::endl;
ofs.close();
```

The output image can be now given to the otb::orthorectificationFilter. Note that this filter allows also to import GCPs from the image metadata, if any.

11.1.4 Limits of the Approach

As you may understand by now, accurate geo-referencing needs accurate DEM and also accurate sensor models and parameters. In the case where we have several images acquired over the same area by different sensors or different geometric configurations, geo-referencing (geographical coordinates) or ortho-rectification (cartographic coordinates) is not usually enough. Indeed, when working with image series we usually want to compare them (fusion, change detection, etc.) at the pixel level.

Since common DEM and sensor parameters do not allow for such an accuracy, we have to use clever strategies to improve the co-registration of the images. The classical one consists in refining the sensor parameters by taking homologous points between the images to co-register. This is called bundle block adjustment and will be implemented in coming versions of OTB.

Even if the model parameters are refined, errors due to DEM accuracy can not be eliminated. In this case, image to image registration can be applied. These approaches are presented in chapters 9 and 10.

11.2 Map Projections

Map projections describe the link between geographic coordinates and cartographic ones. So map projections allow to represent a 2-dimensional manifold of a 3-dimensional space (the Earth surface) in a 2-dimensional space (a map which used to be a sheet of paper!). This geometrical transformation doesn't have a unique solution, so over the cartography history, every country or region in the world has been able to express the belief of being the center of the universe. In other words, every cartographic projection tries to minimize the distortions of the 3D to 2D transformation for a given point of the Earth surface[1].

In OTB the `otb::MapProjection` class is derived from the `itk::Transform` class, so the coordinate transformation points are overloaded with map projection equations. The `otb::MapProjection` class is templated over the type of cartographic projection, which is provided by the OSSIM library. In order to hide the complexity of the approach, some type definitions for the more common projections are given in the file `otbMapProjections.h` file.

Sometimes, you don't know at compile time what map projection you will need in your application. In this case, the `otb::GenericMapProjection` allow you to set the map projection at run-time by passing the WKT identification for the projection.

The source code for this example can be found in the file
`Examples/Projections/MapProjectionExample.cxx`.

Map projection is an important issue when working with satellite images. In the orthorectification

[1] We proposed to optimize an OTB map projection for Toulouse, but we didn't get any help from OTB users.

process, converting between geographic and cartographic coordinates is a key step. In this process, everything is integrated and you don't need to know the details.

However, sometimes, you need to go hands-on and find out the nitty-gritty details. This example shows you how to play with map projections in OTB and how to convert coordinates. In most cases, the underlying work is done by OSSIM.

First, we start by including the otbMapProjections header. In this file, over 30 projections are defined and ready to use. It is easy to add new one.

The otbGenericMapProjection enables you to instanciate a map projection from a WKT (Well Known Text) string, which is popular with OGR for example.

```
#include "otbMapProjections.h"
#include "otbGenericMapProjection.h"
```

We retrieve the command line parameters and put them in the correct variables. The transforms are going to work with an `itk::Point`.

```
  const char * outFileName = argv[1];

  itk::Point<double, 2> point;
  point[0] = 1.4835345;
  point[1] = 43.55968261;
```

The output of this program will be saved in a text file. We also want to make sure that the precision of the digits will be enough.

```
  std::ofstream file;
  file.open(outFileName);
  file << std::setprecision(15);
```

We can now instantiate our first map projection. Here, it is a UTM projection. We also need to provide the information about the zone and the hemisphere for the projection. These are specific to the UTM projection.

```
  otb::UtmForwardProjection::Pointer utmProjection
    = otb::UtmForwardProjection::New();
  utmProjection->SetZone(31);
  utmProjection->SetHemisphere('N');
```

The TransformPoint() method returns the coordinates of the point in the new projection.

```
  file << "Forward UTM projection: " << std::endl;
  file << point << " -> ";
  file << utmProjection->TransformPoint(point);
  file << std::endl << std::endl;
```

We follow the same path for the Lambert93 projection:

```
otb::Lambert93ForwardProjection::Pointer lambertProjection
  = otb::Lambert93ForwardProjection::New();

file << "Forward Lambert93 projection: " << std::endl;
file << point << " -> ";
file << lambertProjection->TransformPoint(point);
file << std::endl << std::endl;
```

If you followed carefully the previous examples, you've noticed that the target projections have been directly coded, which means that they can't be changed at run-time. What happens if you don't know the target projection when you're writing the program? It can depend on some input provided by the user (image, shapefile).

In this situation, you can use the `otb::GenericMapProjection`. It will accept a string to set the projection. This string should be in the WKT format.

For example:

```
std::string projectionRefWkt = "PROJCS[\"UTM Zone 31, Northern Hemisphere\","
                               "GEOGCS[\"WGS 84\", DATUM[\"WGS_1984\", SPHEROID[\"WGS 84\", 6378137,
                               "AUTHORITY[\"EPSG\",\"7030\"]], TOWGS84[0, 0, 0, 0, 0, 0, 0],"
                               "AUTHORITY[\"EPSG\",\"6326\"]], PRIMEM[\"Greenwich\", 0, AUTHORITY[\"
                               "UNIT[\"degree\", 0.0174532925199433, AUTHORITY[\"EPSG\",\"9108\"]],"
                               "AXIS[\"Lat\", NORTH], AXIS[\"Long\", EAST],"
                               "AUTHORITY[\"EPSG\",\"4326\"]], PROJECTION[\"Transverse_Mercator\"],"
                               "PARAMETER[\"latitude_of_origin\", 0], PARAMETER[\"central_meridian\"
                               "PARAMETER[\"scale_factor\", 0.9996], PARAMETER[\"false_easting\", 50
                               "PARAMETER[\"false_northing\", 0], UNIT[\"Meter\", 1]]";
```

This string is then passed to the projection using the `SetWkt()` method.

```
typedef otb::GenericMapProjection<otb::TransformDirection::FORWARD> GenericMapProjection;
GenericMapProjection::Pointer genericMapProjection =
  GenericMapProjection::New();
genericMapProjection->SetWkt(projectionRefWkt);

file << "Forward generic projection: " << std::endl;
file << point << " -> ";
file << genericMapProjection->TransformPoint(point);
file << std::endl << std::endl;
```

And of course, we don't forget to close the file:

```
file.close();
```

The final output of the program should be:

```
Forward UTM projection:
    [1.4835345, 43.55968261] -> [377522.448427013, 4824086.71129131]
```

```
Forward Lambert93 projection:
   [1.4835345, 43.55968261] -> [577437.889798954, 6274578.791561]

Forward generic projection:
   [1.4835345, 43.55968261] -> [377522.448427013, 4824086.71129131]
```

You will seldom use a map projection by itself, but rather in an ortho-rectification framework. An example is given in the next section.

11.3 Orthorectification with OTB

The source code for this example can be found in the file
`Examples/Projections/OrthoRectificationExample.cxx`.

This example demonstrates the use of the `otb::OrthoRectificationFilter`. This filter is intended to orthorectify images which are in a distributor format with the appropriate meta-data describing the sensor model. In this example, we will choose to use an UTM projection for the output image.

The first step toward the use of these filters is to include the proper header files: the one for the ortho-rectification filter and the one defining the different projections available in OTB.

```
#include "otbOrthoRectificationFilter.h"
#include "otbMapProjections.h"
```

We will start by defining the types for the images, the image file reader and the image file writer. The writer will be a `otb::ImageFileWriter` which will allow us to set the number of stream divisions we want to apply when writing the output image, which can be very large.

```
  typedef otb::Image<int, 2>                              ImageType;
  typedef otb::VectorImage<int, 2>                        VectorImageType;
  typedef otb::ImageFileReader<VectorImageType>           ReaderType;
  typedef otb::ImageFileWriter<VectorImageType> WriterType;

  ReaderType::Pointer reader = ReaderType::New();
  WriterType::Pointer writer = WriterType::New();

  reader->SetFileName(argv[1]);
  writer->SetFileName(argv[2]);
```

We can now proceed to declare the type for the ortho-rectification filter. The class `otb::OrthoRectificationFilter` is templated over the input and the output image types as well as over the cartographic projection. We define therefore the type of the projection we want, which is an UTM projection for this case.

```
typedef otb::UtmInverseProjection utmMapProjectionType;
typedef otb::OrthoRectificationFilter<VectorImageType, VectorImageType,
    utmMapProjectionType>
OrthoRectifFilterType;

OrthoRectifFilterType::Pointer orthoRectifFilter =
  OrthoRectifFilterType::New();
```

Now we need to instanciate the map projection, set the *zone* and *hemisphere* parameters and pass this projection to the orthorectification filter.

```
utmMapProjectionType::Pointer utmMapProjection =
  utmMapProjectionType::New();
utmMapProjection->SetZone(atoi(argv[3]));
utmMapProjection->SetHemisphere(*(argv[4]));
orthoRectifFilter->SetMapProjection(utmMapProjection);
```

We then wire the input image to the orthorectification filter.

```
orthoRectifFilter->SetInput(reader->GetOutput());
```

Using the user-provided information, we define the output region for the image generated by the orthorectification filter. We also define the spacing of the deformation grid where actual deformation values are estimated. Choosing a bigger deformation field spacing will speed up computation.

```
ImageType::IndexType start;
start[0] = 0;
start[1] = 0;
orthoRectifFilter->SetOutputStartIndex(start);

ImageType::SizeType size;
size[0] = atoi(argv[7]);
size[1] = atoi(argv[8]);
orthoRectifFilter->SetOutputSize(size);

ImageType::SpacingType spacing;
spacing[0] = atof(argv[9]);
spacing[1] = atof(argv[10]);
orthoRectifFilter->SetOutputSpacing(spacing);

ImageType::SpacingType gridSpacing;
gridSpacing[0] = 2.*atof(argv[9]);
gridSpacing[1] = 2.*atof(argv[10]);
orthoRectifFilter->SetDisplacementFieldSpacing(gridSpacing);

ImageType::PointType origin;
origin[0] = strtod(argv[5], NULL);
origin[1] = strtod(argv[6], NULL);
orthoRectifFilter->SetOutputOrigin(origin);
```

We can now set plug the ortho-rectification filter to the writer and set the number of tiles we want to split the output image in for the writing step.

```
writer->SetInput(orthoRectifFilter->GetOutput());

writer->SetAutomaticTiledStreaming();
```

Finally, we trigger the pipeline execution by calling the `Update()` method on the writer. Please note that the ortho-rectification filter is derived from the `otb::StreamingResampleImageFilter` in order to be able to compute the input image regions which are needed to build the output image. Since the resampler applies a geometric transformation (scale, rotation, etc.), this region computation is not trivial.

```
writer->Update();
```

11.4 Vector data projection manipulation

The source code for this example can be found in the file
`Examples/Projections/VectorDataProjectionExample.cxx`.

Let's assume that you have a KML file (hence in geographical coordinates) that you would like to superpose to some image with a specific map projection. Of course, you could use the handy ogr2ogr tool to do that, but it won't integrate so seamlessly into your OTB application.

You can also suppose that the image on which you want to superpose the data is not in a specific map projection but a raw image from a particular sensor. Thanks to OTB, the same code below will be able to do the appropriate conversion.

This example demonstrates the use of the `otb::VectorDataProjectionFilter`.

Declare the vector data type that you would like to use in your application.

```
typedef otb::VectorData<double> InputVectorDataType;
typedef otb::VectorData<double> OutputVectorDataType;
```

Declare and instantiate the vector data reader: `otb::VectorDataFileReader`. The call to the `UpdateOutputInformation()` method fill up the header information.

```
typedef otb::VectorDataFileReader<InputVectorDataType>
VectorDataFileReaderType;
VectorDataFileReaderType::Pointer reader = VectorDataFileReaderType::New();

reader->SetFileName(argv[1]);
reader->UpdateOutputInformation();
```

We need the image only to retrieve its projection information, i.e. map projection or sensor model parameters. Hence, the image pixels won't be read, only the header information using the `UpdateOutputInformation()` method.

```
typedef otb::Image<unsigned short int, 2> ImageType;
typedef otb::ImageFileReader<ImageType>   ImageReaderType;
ImageReaderType::Pointer imageReader = ImageReaderType::New();
imageReader->SetFileName(argv[2]);
imageReader->UpdateOutputInformation();
```

The `otb::VectorDataProjectionFilter` will do the work of converting the vector data coordinates. It is usually a good idea to use it when you design applications reading or saving vector data.

```
typedef otb::VectorDataProjectionFilter<InputVectorDataType,
    OutputVectorDataType>
VectorDataFilterType;
VectorDataFilterType::Pointer vectorDataProjection =
  VectorDataFilterType::New();
```

Information concerning the original projection of the vector data will be automatically retrieved from the metadata. Nothing else is needed from you:

```
vectorDataProjection->SetInput(reader->GetOutput());
```

Information about the target projection is retrieved directly from the image:

```
vectorDataProjection->SetOutputKeywordList(
  imageReader->GetOutput()->GetImageKeywordlist());
vectorDataProjection->SetOutputOrigin(
  imageReader->GetOutput()->GetOrigin());
vectorDataProjection->SetOutputSpacing(
  imageReader->GetOutput()->GetSpacing());
vectorDataProjection->SetOutputProjectionRef(
  imageReader->GetOutput()->GetProjectionRef());
```

Finally, the result is saved into a new vector file.

```
typedef otb::VectorDataFileWriter<OutputVectorDataType>
VectorDataFileWriterType;
VectorDataFileWriterType::Pointer writer = VectorDataFileWriterType::New();
writer->SetFileName(argv[3]);
writer->SetInput(vectorDataProjection->GetOutput());
writer->Update();
```

It is worth noting that none of this code is specific to the vector data format. Whether you pass a shapefile, or a KML file, the correct driver will be automatically instantiated.

11.5 Geometries projection manipulation

The source code for this example can be found in the file
`Examples/Projections/GeometriesProjectionExample.cxx`.

Instead of using `otb::VectorData` to apply projections as explained in 11.4, we can also *directly* work on OGR data types thanks to `otb::GeometriesProjectionFilter`.

This example demonstrates how to proceed with this alternative set of vector data types.

Declare the geometries type that you would like to use in your application. Unlike `otb::VectorData`, `otb::GeometriesSet` is a single type for any kind of geometries set (OGR data source, or OGR layer).

```
typedef otb::GeometriesSet InputGeometriesType;
typedef otb::GeometriesSet OutputGeometriesType;
```

First, declare and instantiate the data source `otb::ogr::DataSource`. Then, encapsulate this data source into a `otb::GeometriesSet`.

```
otb::ogr::DataSource::Pointer input = otb::ogr::DataSource::New(
  argv[1], otb::ogr::DataSource::Modes::Read);
InputGeometriesType::Pointer in_set = InputGeometriesType::New(input);
```

We need the image only to retrieve its projection information, i.e. map projection or sensor model parameters. Hence, the image pixels won't be read, only the header information using the `UpdateOutputInformation()` method.

```
typedef otb::Image<unsigned short int, 2> ImageType;
typedef otb::ImageFileReader<ImageType>   ImageReaderType;
ImageReaderType::Pointer imageReader = ImageReaderType::New();
imageReader->SetFileName(argv[2]);
imageReader->UpdateOutputInformation();
```

The `otb::GeometriesProjectionFilter` will do the work of converting the geometries coordinates. It is usually a good idea to use it when you design applications reading or saving vector data.

```
typedef otb::GeometriesProjectionFilter GeometriesFilterType;
GeometriesFilterType::Pointer filter = GeometriesFilterType::New();
```

Information concerning the original projection of the vector data will be automatically retrieved from the metadata. Nothing else is needed from you:

```
filter->SetInput(in_set);
```

Information about the target projection is retrieved directly from the image:

```
// necessary for sensors
filter->SetOutputKeywordList(imageReader->GetOutput()->GetImageKeywordlist());
// necessary for sensors
filter->SetOutputOrigin(imageReader->GetOutput()->GetOrigin());
// necessary for sensors
filter->SetOutputSpacing(imageReader->GetOutput()->GetSpacing());
// ~ wkt
filter->SetOutputProjectionRef( imageReader->GetOutput()->GetProjectionRef());
```

Finally, the result is saved into a new vector file. Unlike other OTB filters, `otb::GeometriesProjectionFilter` expects to be given a valid output geometries set where to store the result of its processing – otherwise the result will be an in-memory data source, and not stored in a file nor a data base.

Then, the processing is started by calling `Update()`. The actual serialization of the results is guaranteed to be completed when the ouput geometries set object goes out of scope, or when `SyncToDisk` is called.

```
otb::ogr::DataSource::Pointer output = otb::ogr::DataSource::New(
  argv[3], otb::ogr::DataSource::Modes::Update_LayerCreateOnly);
OutputGeometriesType::Pointer out_set = OutputGeometriesType::New(output);

filter->SetOutput(out_set);
filter->Update();
```

Once again, it is worth noting that none of this code is specific to the vector data format. Whether you pass a shapefile, or a KML file, the correct driver will be automatically instantiated.

11.6 Elevation management with OTB

The source code for this example can be found in the file `Examples/IO/DEMHandlerExample.cxx`.

OTB relies on OSSIM for elevation handling. Since release 3.16, there is a single configuration class `otb::DEMHandler` to manage elevation (in image projections or localization functions for example). This configuration is managed by the a proper instanciation and parameters setting of this class. These instanciations must be done before any call to geometric filters or functionalities. Ossim internal accesses to elevation are also configured by this class and this will ensure consistency throughout the library.

This class is a singleton, the New() method is deprecated and will be removed in future release. We need to use the `Instance()` method instead.

```
otb::DEMHandler::Pointer demHandler = otb::DEMHandler::Instance();
```

It allows to configure a directory containing DEM tiles (DTED or SRTM supported) using the `OpenDEMDirectory()` method. The `OpenGeoidFile()` method allows to input a geoid file as well. Last, a default height above ellipsoid can be set using the `SetDefaultHeightAboveEllipsoid()` method.

```
demHandler->SetDefaultHeightAboveEllipsoid(defaultHeight);

if(!demHandler->IsValidDEMDirectory(demdir.c_str()))
  {
  std::cerr<<"IsValidDEMDirectory("<<demdir<<") = false"<<std::endl;
  fail = true;
```

```
  }

demHandler->OpenDEMDirectory(demdir);
demHandler->OpenGeoidFile(geoid);
```

We can now retrieve height above ellipsoid or height above Mean Sea Level (MSL) using the methods `GetHeightAboveEllipsoid()` and `GetHeightAboveMSL()`. Outputs of these methods depend on the configuration of the class `otb::DEMHandler` and the different cases are:

For `GetHeightAboveEllipsoid()`:

- DEM and geoid both available: $dem\_value + geoid\_offset$
- No DEM but geoid available: geoid_offset
- DEM available, but no geoid: dem_value
- No DEM and no geoid available: default height above ellipsoid

For `GetHeightAboveMSL()`:

- DEM and geoid both available: srtm_value
- No DEM but geoid available: 0
- DEM available, but no geoid: srtm_value
- No DEM and no geoid available: 0

```
otb::DEMHandler::PointType point;
point[0] = longitude;
point[1] = latitude;

double height = -32768;

height = demHandler->GetHeightAboveMSL(point);
std::cout<<"height above MSL ("<<longitude<<","
         <<latitude<<") = "<<height<<" meters"<<std::endl;

height = demHandler->GetHeightAboveEllipsoid(point);
std::cout<<"height above ellipsoid ("<<longitude
         <<", "<<latitude<<") = "<<height<<" meters"<<std::endl;
```

Note that OSSIM internal calls for sensor modelling use the height above ellipsoid, and follow the same logic as the `GetHeightAboveEllipsoid()` method.

11.7 Vector data area extraction

The source code for this example can be found in the file
`Examples/Projections/VectorDataExtractROIExample.cxx`.

There is some vector data sets widely available on the internet. These data sets can be huge, covering an entire country, with hundreds of thousands objects.

Most of the time, you won't be interested in the whole area and would like to focuss only on the area corresponding to your satellite image.

The `otb::VectorDataExtractROI` is able to extract the area corresponding to your satellite image, even if the image is still in sensor geometry (provided the sensor model is supported by OTB). Let's see how we can do that.

This example demonstrates the use of the `otb::VectorDataExtractROI`.

After the usual declaration (you can check the source file for the details), we can declare the `otb::VectorDataExtractROI`:

```
typedef otb::VectorDataExtractROI<VectorDataType> FilterType;
FilterType::Pointer filter = FilterType::New();
```

Then, we need to specify the region to extract. This region is a bit special as it contains also information related to its reference system (cartographic projection or sensor model projection). We retrieve all these information from the image we gave as an input.

```
TypedRegion            region;
TypedRegion::SizeType  size;
TypedRegion::IndexType index;

size[0]  = imageReader->GetOutput()->GetLargestPossibleRegion().GetSize()[0]
           * imageReader->GetOutput()->GetSpacing()[0];
size[1]  = imageReader->GetOutput()->GetLargestPossibleRegion().GetSize()[1]
           * imageReader->GetOutput()->GetSpacing()[1];
index[0] = imageReader->GetOutput()->GetOrigin()[0]
           - 0.5 * imageReader->GetOutput()->GetSpacing()[0];
index[1] = imageReader->GetOutput()->GetOrigin()[1]
           - 0.5 * imageReader->GetOutput()->GetSpacing()[1];
region.SetSize(size);
region.SetOrigin(index);

otb::ImageMetadataInterfaceBase::Pointer imageMetadataInterface
  = otb::ImageMetadataInterfaceFactory::CreateIMI(
  imageReader->GetOutput()->GetMetaDataDictionary());
region.SetRegionProjection(
  imageMetadataInterface->GetProjectionRef());

region.SetKeywordList(imageReader->GetOutput()->GetImageKeywordlist());

filter->SetRegion(region);
```

And finally, we can plug the filter in the pipeline:

```
filter->SetInput(reader->GetOutput());
writer->SetInput(filter->GetOutput());
```

CHAPTER

TWELVE

RADIOMETRY

Remote sensing is not just a matter of taking pictures, but also – mostly – a matter of measuring physical values. In order to properly deal with physical magnitudes, the numerical values provided by the sensors have to be calibrated. After that, several indices with physical meaning can be computed.

12.1 Radiometric Indices

12.1.1 Introduction

With multispectral sensors, several indices can be computed, combining several spectral bands to show features that are not obvious using only one band. Indices can show:

- Vegetation (Tab 12.1)
- Soil (Tab 12.2)
- Water (Tab 12.3)
- Built up areas (Tab 12.4)

A vegetation index is a quantitative measure used to measure biomass or vegetative vigor, usually formed from combinations of several spectral bands, whose values are added, divided, or multiplied in order to yield a single value that indicates the amount or vigor of vegetation.

Numerous indices are available in OTB and are listed in table 12.1 to 12.4 with their references.

The use of the different indices is very similar, and only few example are given in the next sections.

NDVI	Normalized Difference Vegetation Index [119]
RVI	Ratio Vegetation Index [103]
PVI	Perpendicular Vegetation Index [116, 144]
SAVI	Soil Adjusted Vegetation Index [64]
TSAVI	Transformed Soil Adjusted Vegetation Index [9, 8]
MSAVI	Modified Soil Adjusted Vegetation Index [112]
MSAVI2	Modified Soil Adjusted Vegetation Index [112]
GEMI	Global Environment Monitoring Index [108]
WDVI	Weighted Difference Vegetation Index [26, 27]
AVI	Angular Vegetation Index [110]
ARVI	Atmospherically Resistant Vegetation Index [78]
TSARVI	Transformed Soil Adjusted Vegetation Index [78]
EVI	Enhanced Vegetation Index [65, 75]
IPVI	Infrared Percentage Vegetation Index [31]
TNDVI	Transformed NDVI [35]

Table 12.1: Vegetation indices

IR	Redness Index [45]
IC	Color Index [45]
IB	Brilliance Index [98]
IB2	Brilliance Index [98]

Table 12.2: Soil indices

12.1.2 NDVI

NDVI was one of the most successful of many attempts to simply and quickly identify vegetated areas and their *condition*, and it remains the most well-known and used index to detect live green plant canopies in multispectral remote sensing data. Once the feasibility to detect vegetation had been demonstrated, users tended to also use the NDVI to quantify the photosynthetic capacity of plant canopies. This, however, can be a rather more complex undertaking if not done properly.

The source code for this example can be found in the file
`Examples/Radiometry/NDVIRAndNIRVegetationIndexImageFilter.cxx`.

The following example illustrates the use of the `otb::RAndNIRIndexImageFilter` with the use of the Normalized Difference Vegatation Index (NDVI). NDVI computes the difference between the NIR channel, noted L_{NIR}, and the red channel, noted L_r radiances reflected from the surface and transmitted through the atmosphere:

$$\mathbf{NDVI} = \frac{L_{NIR} - L_r}{L_{NIR} + L_r} \tag{12.1}$$

The following classes provide similar functionality:

SRWI	Simple Ratio Water Index [150]
NDWI	Normalized Difference Water Index [20]
NDWI2	Normalized Difference Water Index [94]
MNDWI	Modified Normalized Difference Water Index [146]
NDPI	Normalized Difference Pond Index [82]
NDTI	Normalized Difference Turbidity Index [82]
SA	Spectral Angle

Table 12.3: Water indices

NDBI	Normalized Difference Built Up Index [97]
ISU	Index Surfaces Built [1]

Table 12.4: Built-up indices

- otb::Functor::RVI
- otb::Functor::PVI
- otb::Functor::SAVI
- otb::Functor::TSAVI
- otb::Functor::MSAVI
- otb::Functor::GEMI
- otb::Functor::WDVI
- otb::Functor::IPVI
- otb::Functor::TNDVI

With the otb::RAndNIRIndexImageFilter class the filter inputs are one channel images: one inmage represents the NIR channel, the the other the NIR channel.

Let's look at the minimal code required to use this algorithm. First, the following header defining the otb::RAndNIRIndexImageFilter class must be included.

```
#include "otbRAndNIRIndexImageFilter.h"
```

The image types are now defined using pixel types the dimension. Input and output images are defined as otb::Image.

```
const unsigned int Dimension = 2;
typedef double                                  InputPixelType;
typedef float                                   OutputPixelType;
typedef otb::Image<InputPixelType, Dimension>  InputRImageType;
typedef otb::Image<InputPixelType, Dimension>  InputNIRImageType;
typedef otb::Image<OutputPixelType, Dimension> OutputImageType;
```

The NDVI (Normalized Difference Vegetation Index) is instantiated using the images pixel type as template parameters. It is implemented as a functor class which will be passed as a parameter to an otb::RAndNIRIndexImageFilter.

```
typedef otb::Functor::NDVI<InputPixelType,
    InputPixelType,
    OutputPixelType>   FunctorType;
```

The otb::RAndNIRIndexImageFilter type is instantiated using the images types and the NDVI functor as template parameters.

```
typedef otb::RAndNIRIndexImageFilter<InputRImageType,
    InputNIRImageType,
    OutputImageType,
    FunctorType>
RAndNIRIndexImageFilterType;
```

Now the input images are set and a name is given to the output image.

```
readerR->SetFileName(argv[1]);
readerNIR->SetFileName(argv[2]);
writer->SetFileName(argv[3]);
```

We set the processing pipeline: filter inputs are linked to the reader output and the filter output is linked to the writer input.

```
filter->SetInputR(readerR->GetOutput());
filter->SetInputNIR(readerNIR->GetOutput());

writer->SetInput(filter->GetOutput());
```

Invocation of the Update() method on the writer triggers the execution of the pipeline. It is recommended to place update() calls in a try/catch block in case errors occur and exceptions are thrown.

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& excep)
  {
  std::cerr << "Exception caught !" << std::endl;
  std::cerr << excep << std::endl;
  }
```

Let's now run this example using as input the images NDVI_3.hdr and NDVI_4.hdr (images kindly and free of charge given by SISA and CNES) provided in the directory Examples/Data.

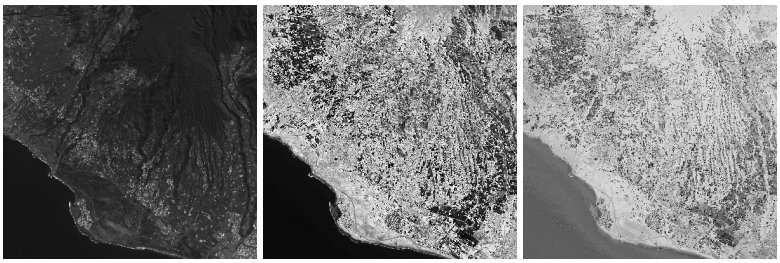


Figure 12.1: NDVI input images on the left (Red channel and NIR channel), on the right the result of the algorithm.

12.1.3 ARVI

The source code for this example can be found in the file
`Examples/Radiometry/ARVIMultiChannelRAndBAndNIRVegetationIndexImageFilter.cxx`.

The following example illustrates the use of the `otb::MultiChannelRAndBAndNIRIndexImageFilter` with the use of the Atmospherically Resistant Vegetation Index (ARVI) `otb::Functor::ARVI`. ARVI is an improved version of the NDVI that is more robust to the atmospheric effect. In addition to the red and NIR channels (used in the NDVI), the ARVI takes advantage of the presence of the blue channel to accomplish a self-correction process for the atmospheric effect on the red channel. For this, it uses the difference in the radiance between the blue and the red channels to correct the radiance in the red channel. Let's define ρ^*_{NIR}, ρ^*_r, ρ^*_b the normalized radiances (that is to say the radiance normalized to reflectance units) of red, blue and NIR channels respectively. ρ^*_{rb} is defined as

$$\rho^*_{rb} = \rho^*_r - \gamma * (\rho^*_b - \rho^*_r) \tag{12.2}$$

The ARVI expression is

$$\mathbf{ARVI} = \frac{\rho^*_{NIR} - \rho^*_{rb}}{\rho^*_{NIR} + \rho^*_{rb}} \tag{12.3}$$

This formula can be simplified with :

$$\mathbf{ARVI} = \frac{L_{NIR} - L_{rb}}{L_{NIR} + L_{rb}} \tag{12.4}$$

For more details, refer to Kaufman and Tanre' work [78].

The following classes provide similar functionality:

- `otb::Functor::TSARVI`

- otb::Functor::EVI

With the otb::MultiChannelRAndBAndNIRIndexImageFilter class the input has to be a multi channel image and the user has to specify index channel of the red, blue and NIR channel.

Let's look at the minimal code required to use this algorithm. First, the following header defining the otb::MultiChannelRAndBAndNIRIndexImageFilter class must be included.

```
#include "otbMultiChannelRAndBAndNIRIndexImageFilter.h"
```

The image types are now defined using pixel types and dimension. The input image is defined as an otb::VectorImage, the output is a otb::Image.

```
const unsigned int Dimension = 2;
typedef double                                          InputPixelType;
typedef float                                           OutputPixelType;
typedef otb::VectorImage<InputPixelType, Dimension> InputImageType;
typedef otb::Image<OutputPixelType, Dimension>      OutputImageType;
```

The ARVI (Atmospherically Resistant Vegetation Index) is instantiated using the image pixel types as template parameters. Note that we also can use other functors which operate with the Red, Blue and Nir channels such as EVI, ARVI and TSARVI.

```
typedef  otb::Functor::ARVI<InputPixelType,
    InputPixelType,
    InputPixelType,
    OutputPixelType>        FunctorType;
```

The otb::MultiChannelRAndBAndNIRIndexImageFilter type is defined using the image types and the ARVI functor as template parameters. We then instantiate the filter itself.

```
typedef otb::MultiChannelRAndBAndNIRIndexImageFilter
<InputImageType,
    OutputImageType,
    FunctorType>
MultiChannelRAndBAndNIRIndexImageFilterType;

MultiChannelRAndBAndNIRIndexImageFilterType::Pointer
  filter = MultiChannelRAndBAndNIRIndexImageFilterType::New();
```

Now the input image is set and a name is given to the output image.

```
reader->SetFileName(argv[1]);
writer->SetFileName(argv[2]);
```

The three used index bands (red, blue and NIR) are declared.

```
filter->SetRedIndex(::atoi(argv[5]));
filter->SetBlueIndex(::atoi(argv[6]));
filter->SetNIRIndex(::atoi(argv[7]));
```

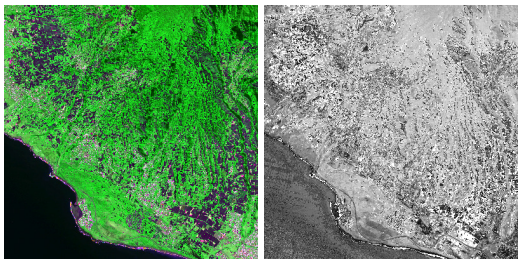


Figure 12.2: ARVI result on the right with the left image in input.

The γ parameter is set. The `otb::MultiChannelRAndBAndNIRIndexImageFilter` class sets the default value of γ to 0.5. This parameter is used to reduce the atmospheric effect on a global scale.

```
filter->GetFunctor().SetGamma(::atof(argv[8]));
```

The filter input is linked to the reader output and the filter output is linked to the writer input.

```
filter->SetInput(reader->GetOutput());

writer->SetInput(filter->GetOutput());
```

The invocation of the `Update()` method on the writer triggers the execution of the pipeline. It is recommended to place update calls in a `try/catch` block in case errors occur and exceptions are thrown.

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& excep)
  {
  std::cerr << "Exception caught !" << std::endl;
  std::cerr << excep << std::endl;
  }
```

Let's now run this example using as input the image `IndexVegetation.hd` (image kindly and free of charge given by SISA and CNES) and γ=0.6 provided in the directory `Examples/Data`.

12.1.4 AVI

The source code for this example can be found in the file
`Examples/Radiometry/AVIMultiChannelRAndGAndNIRVegetationIndexImageFilter.cxx`.

The following example illustrates the use of the otb::MultiChannelRAndGAndNIR VegetationIndexImageFilter with the use of the Angular Vegetation Index (AVI). The equation for the Angular

Vegetation Index involves the gren, red and near infra-red bands. λ_1, λ_2 and λ_3 are the mid-band wavelengths for the green, red and NIR bands and $\tan^{-1}$ is the arctangent function.

The AVI expression is

$$\mathbf{A_1} = \frac{\lambda_3 - \lambda_2}{\lambda_2} \tag{12.5}$$

$$\mathbf{A_2} = \frac{\lambda_2 - \lambda_1}{\lambda_2} \tag{12.6}$$

$$\mathbf{AVI} = \tan^{-1}\left(\frac{A_1}{NIR - R}\right) + \tan^{-1}\left(\frac{A_2}{G - R}\right) \tag{12.7}$$

For more details, refer to Plummer work [110].

With the `otb::MultiChannelRAndGAndNIRIndexImageFilter` class the input has to be a multi channel image and the user has to specify the channel index of the red, green and NIR channel.

Let's look at the minimal code required to use this algorithm. First, the following header defining the `otb::MultiChannelRAndGAndNIRIndexImageFilter` class must be included.

```
#include "otbMultiChannelRAndGAndNIRIndexImageFilter.h"
```

The image types are now defined using pixel types and dimension. The input image is defined as an `otb::VectorImage`, the output is a `otb::Image`.

```
const unsigned int Dimension = 2;
typedef double                                          InputPixelType;
typedef float                                           OutputPixelType;
typedef otb::VectorImage<InputPixelType, Dimension>     InputImageType;
typedef otb::Image<OutputPixelType, Dimension>          OutputImageType;
```

The AVI (Angular Vegetation Index) is instantiated using the image pixel types as template parameters.

```
typedef  otb::Functor::AVI<InputPixelType, InputPixelType,
    InputPixelType,  OutputPixelType> FunctorType;
```

The `otb::MultiChannelRAndGAndNIRIndexImageFilter` type is defined using the image types and the AVI functor as template parameters. We then instantiate the filter itself.

```
typedef otb::MultiChannelRAndGAndNIRIndexImageFilter
<InputImageType, OutputImageType, FunctorType>
MultiChannelRAndGAndNIRIndexImageFilterType;

MultiChannelRAndGAndNIRIndexImageFilterType::Pointer
  filter = MultiChannelRAndGAndNIRIndexImageFilterType::New();
```

Now the input image is set and a name is given to the output image.

```
reader->SetFileName(argv[1]);
writer->SetFileName(argv[2]);
```

The three used index bands (red, green and NIR) are declared.

```
filter->SetRedIndex(::atoi(argv[5]));
filter->SetGreenIndex(::atoi(argv[6]));
filter->SetNIRIndex(::atoi(argv[7]));
```

The λ R, G and NIR parameters are set. The `otb::MultiChannelRAndGAndNIRIndexImageFilter` class sets the default values of λ to 660, 560 and 830.

```
filter->GetFunctor().SetLambdaR(::atof(argv[8]));
filter->GetFunctor().SetLambdaG(::atof(argv[9]));
filter->GetFunctor().SetLambdaNir(::atof(argv[10]));
```

The filter input is linked to the reader output and the filter output is linked to the writer input.

```
filter->SetInput(reader->GetOutput());

writer->SetInput(filter->GetOutput());
```

The invocation of the `Update()` method on the writer triggers the execution of the pipeline. It is recommended to place update calls in a `try/catch` block in case errors occur and exceptions are thrown.

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& excep)
  {
  std::cerr << "Exception caught !" << std::endl;
  std::cerr << excep << std::endl;
  }
```

Let's now run this example using as input the image `verySmallFSATSW.tif` provided in the directory `Examples/Data`.

12.2 Atmospheric Corrections

The source code for this example can be found in the file
`Examples/Radiometry/AtmosphericCorrectionSequencement.cxx`.

The following example illustrates the application of atmospheric corrections to an optical multispectral image similar to Pleiades. These corrections are made in four steps :

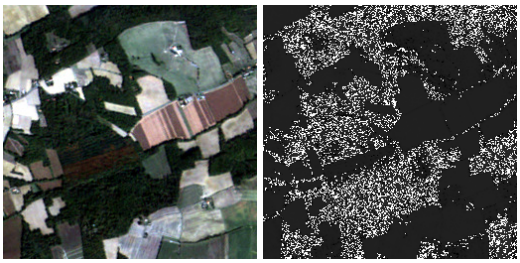


Figure 12.3: AVI result on the right with the left image in input.

- digital number to luminance correction;
- luminance to refletance image conversion;
- atmospheric correction for TOA (top of atmosphere) to TOC (top of canopy) reflectance estimation;
- correction of the adjacency effects taking into account the neighborhood contribution.

The manipulation of each class used for the different steps and the link with the 6S radiometry library will be explained.

Let's look at the minimal code required to use this algorithm. First, the following header defining the `otb::AtmosphericCorrectionSequencement` class must be included. For the numerical to luminance image, luminance to refletance image, and reflectance to atmospheric correction image corrections and the neighborhood correction, four header files are required.

```
#include "otbImageToLuminanceImageFilter.h"
#include "otbLuminanceToReflectanceImageFilter.h"
#include "otbReflectanceToSurfaceReflectanceImageFilter.h"
#include "otbSurfaceAdjacencyEffect6SCorrectionSchemeFilter.h"
```

This chain uses the 6S radiative transfer code to compute radiometric parameters. To manipulate 6S data, three classes are needed (the first one to store the metadata, the second one that calls 6S class and generates the information which will be stored in the last one).

```
#include "otbAtmosphericCorrectionParameters.h"
#include "otbAtmosphericCorrectionParametersTo6SAtmosphericRadiativeTerms.h"
#include "otbAtmosphericRadiativeTerms.h"
```

Image types are now defined using pixel types and dimension. The input image is defined as an `otb::VectorImage`, the output image is a `otb::VectorImage`. To simplify, input and output image types are the same one.

```
  const unsigned int Dimension = 2;
  typedef double                                PixelType;
  typedef otb::VectorImage<PixelType, Dimension> ImageType;
```

The `GenerateOutputInformation()` reader method is called to know the number of component per pixel of the image. It is recommended to place `GenerateOutputInformation` calls in a `try/catch` block in case errors occur and exceptions are thrown.

```
reader->SetFileName(argv[1]);
try
  {
  reader->GenerateOutputInformation();
  }
catch (itk::ExceptionObject& excep)
  {
  std::cerr << "Exception caught !" << std::endl;
  std::cerr << excep << std::endl;
  }
```

The `otb::ImageToLuminanceImageFilter` type is defined and instancied. This class uses a functor applied to each component of each pixel ($\mathbf{X^k}$) whose formula is:

$$\mathbf{L^k_{TOA}} = \frac{X^k}{\alpha_k} + \beta_k. \tag{12.8}$$

Where :

- $\mathbf{L^k_{TOA}}$ is the incident luminance (in $W.m^{-2}.sr^{-1}.\mu m^{-1}$);
- $\mathbf{X^k}$ is the measured digital number (ie. the input image pixel component);
- α_k is the absolute calibration gain for the channel k;
- β_k is the absolute calibration bias for the channel k.

```
typedef otb::ImageToLuminanceImageFilter<ImageType, ImageType>
ImageToLuminanceImageFilterType;

ImageToLuminanceImageFilterType::Pointer filterImageToLuminance
  = ImageToLuminanceImageFilterType::New();
```

Here, α and β are read from an ASCII file given in input, stored in a vector and passed to the class.

```
filterImageToLuminance->SetAlpha(alpha);
filterImageToLuminance->SetBeta(beta);
```

The `otb::LuminanceToReflectanceImageFilter` type is defined and instancied. This class used a functor applied to each component of each pixel of the luminance filter output ($\mathbf{L^k_{TOA}}$):

$$\rho^k_{TOA} = \frac{\pi.\mathbf{L^k_{TOA}}}{E^k_S.cos(\theta_S).d/d_0}. \tag{12.9}$$

Where :

- $\rho^{\mathbf{k}}_{\mathbf{TOA}}$ is the reflectance measured by the sensor;
- θ_S is the zenithal solar angle in degrees;
- E^k_S is the solar illumination out of the atmosphere measured at a distance d_0 from the Earth;
- d/d_0 is the ratio between the Earth-Sun distance at the acquisition date and the mean Earth-Sun distance. The ratio can be directly given to the class or computed using a 6S routine. In the last case (that is the one of this example), the user has to precise the month and the day of the acquisition.

```
typedef otb::LuminanceToReflectanceImageFilter<ImageType, ImageType>
LuminanceToReflectanceImageFilterType;
LuminanceToReflectanceImageFilterType::Pointer filterLuminanceToReflectance
  = LuminanceToReflectanceImageFilterType::New();
```

The solar illumination is read from a ASCII file given in input, stored in a vector and given to the class. Day, month and zenital solar angle are inputs and can be directly given to the class.

```
filterLuminanceToReflectance->SetZenithalSolarAngle(
  static_cast<double>(atof(argv[6])));
filterLuminanceToReflectance->SetDay(atoi(argv[7]));
filterLuminanceToReflectance->SetMonth(atoi(argv[8]));
filterLuminanceToReflectance->SetSolarIllumination(solarIllumination);
```

At this step of the chain, radiometric informations are nedeed. Those informations will be computed from different parameters stored in a `otb::AtmosphericCorrectionParameters` class intance. This *container* will be given to an `otb::AtmosphericCorrectionParametersTo6SAtmosphericRadiativeTerms` class instance which will call a 6S routine that will compute the needed radiometric informations and store them in a `otb::AtmosphericRadiativeTerms` class instance. For this, `otb::AtmosphericCorrectionParametersTo6SAtmosphericRadiativeTerms` `otb::AtmosphericCorrectionParameters` and `otb::AtmosphericRadiativeTerms` types are defined and instancied.

```
typedef otb::AtmosphericCorrectionParametersTo6SAtmosphericRadiativeTerms
AtmosphericCorrectionParametersTo6SRadiativeTermsType;

typedef otb::AtmosphericCorrectionParameters
AtmosphericCorrectionParametersType;

typedef otb::AtmosphericRadiativeTerms
AtmosphericRadiativeTermsType;
```

The `otb::AtmosphericCorrectionParameters` class needs several parameters :

- The zenithal and azimutal solar angles that describe the solar incidence configuration (in degrees);

- The zenithal and azimuthal viewing angles that describe the viewing direction (in degrees);
- The month and the day of the acquisition;
- The atmospheric pressure;
- The water vapor amount, that is, the total water vapor content over vertical atmospheric column;
- The ozone amount that is the Stratospheric ozone layer content;
- The aerosol model that is the kind of particles (no aerosol, continental, maritime, urban, desertic);
- The aerosol optical thickness at 550 nm that is the is the Radiative impact of aerosol for the reference wavelength 550 nm;
- The filter function that is the values of the filter function for one spectral band, from λ_{inf} to λ_{sup} by step of 2.5 nm. One filter function by channel is required. This last parameter are read in text files, the other one are directly given to the class.

```
dataAtmosphericCorrectionParameters->SetSolarZenithalAngle(
  static_cast<double>(atof(argv[6])));

dataAtmosphericCorrectionParameters->SetSolarAzimutalAngle(
  static_cast<double>(atof(argv[9])));

dataAtmosphericCorrectionParameters->SetViewingZenithalAngle(
  static_cast<double>(atof(argv[10])));

dataAtmosphericCorrectionParameters->SetViewingAzimutalAngle(
  static_cast<double>(atof(argv[11])));

dataAtmosphericCorrectionParameters->SetMonth(atoi(argv[8]));

dataAtmosphericCorrectionParameters->SetDay(atoi(argv[7]));

dataAtmosphericCorrectionParameters->SetAtmosphericPressure(
  static_cast<double>(atof(argv[12])));

dataAtmosphericCorrectionParameters->SetWaterVaporAmount(
  static_cast<double>(atof(argv[13])));

dataAtmosphericCorrectionParameters->SetOzoneAmount(
  static_cast<double>(atof(argv[14])));

AerosolModelType aerosolModel =
  static_cast<AerosolModelType>(::atoi(argv[15]));

dataAtmosphericCorrectionParameters->SetAerosolModel(aerosolModel);

dataAtmosphericCorrectionParameters->SetAerosolOptical(
  static_cast<double>(atof(argv[16])));
```

Once those parameters are loaded and stored in the AtmosphericCorrectionParameters instance class, it is given in input of an instance of AtmosphericCorrectionParametersTo6SAtmosphericRadiativeTerms that will compute the needed radiometric informations.

```
AtmosphericCorrectionParametersTo6SRadiativeTermsType::Pointer
  filterAtmosphericCorrectionParametersTo6SRadiativeTerms =
  AtmosphericCorrectionParametersTo6SRadiativeTermsType::New();

filterAtmosphericCorrectionParametersTo6SRadiativeTerms->SetInput(
  dataAtmosphericCorrectionParameters);

filterAtmosphericCorrectionParametersTo6SRadiativeTerms->Update();
```

The output of this class will be an instance of the AtmosphericRadiativeTerms class. This class contains (for each channel of the image)

- The Intrinsic atmospheric reflectance that takes into account for the molecular scattering and the aerosol scattering attenuated by water vapor absorption;
- The spherical albedo of the atmosphere;
- The total gaseous transmission (for all species);
- The total transmittance of the atmosphere from sun to ground (downward transmittance) and from ground to space sensor (upward transmittance).

Atmospheric corrections can now start. First, an instance of `otb::ReflectanceToSurfaceReflectanceImageFilter` is created.

```
typedef otb::ReflectanceToSurfaceReflectanceImageFilter<ImageType,
    ImageType>
ReflectanceToSurfaceReflectanceImageFilterType;

ReflectanceToSurfaceReflectanceImageFilterType::Pointer
  filterReflectanceToSurfaceReflectanceImageFilter
  = ReflectanceToSurfaceReflectanceImageFilterType::New();
```

The aim of the atmospheric correction is to invert the surface reflectance (for each pixel of the input image) from the TOA reflectance and from simulations of the atmospheric radiative functions corresponding to the geometrical conditions of the observation and to the atmospheric components. The process required to be applied on each pixel of the image, band by band with the following formula:

$$\rho_S^{unif} = \frac{\mathbf{A}}{1 + Sx\mathbf{A}} \tag{12.10}$$

Where,

$$\mathbf{A} = \frac{\rho_{TOA} - \rho_{atm}}{T(\mu_S).T(\mu_V).t_g^{allgas}} \tag{12.11}$$

With :

- ρ_{TOA} is the reflectance at the top of the atmosphere;
- ρ_S^{unif} is the ground reflectance under assumption of a lambertian surface and an uniform environment;
- ρ_{atm} is the intrinsic atmospheric reflectance;
- t_g^{allgas} is the spherical albedo of the atmosphere;
- $T(\mu_S)$ is the downward transmittance;
- $T(\mu_V)$ is the upward transmittance.

All those parameters are contained in the AtmosphericCorrectionParametersTo6SRadiativeTerms output.

```
filterReflectanceToSurfaceReflectanceImageFilter->
SetAtmosphericRadiativeTerms(
  filterAtmosphericCorrectionParametersTo6SRadiativeTerms->GetOutput());
```

Next (and last step) is the neighborhood correction. For this, the SurfaceAdjacencyEffect6SCorrectionSchemeFilter class is used. The previous surface reflectance inversion is performed under the assumption of a homogeneous ground environment. The following step allows to correct the adjacency effect on the radiometry of pixels. The method is based on the decomposition of the observed signal as the summation of the own contribution of the target pixel and of the contribution of neighbored pixels moderated by their distance to the target pixel. A simplified relation may be :

$$\rho S = \frac{\rho_S^{unif}.T(\mu_V) - <\rho S>.t_d(\mu_V)}{exp(-\delta/\mu_V)} \tag{12.12}$$

With :

- ρ_S^{unif} is the ground reflectance under assumption of an homogeneous environment;
- $T(\mu_V)$ is the upward transmittance;
- $t_d(\mu_S)$ is the upward diffus transmittance;
- $exp(-\delta/\mu_V)$ is the upward direct transmittance;
- ρ_S is the environment contribution to the pixel target reflectance in the total observed signal.

$$\rho S = \sum j \sum if(r(i,j)) \times \rho_S^{unif}(i,j) \tag{12.13}$$

where,

- r(i, j) is the distance between the pixel(i, j) and the central pixel of the window in *km*;
- f(r) is the global environment function.

$$f(r) = \frac{t_d^R(\mu_V).f_R(r) + t_d^A(\mu_V).f_A(r)}{t_d(\mu_V)} \tag{12.14}$$

The neighborhood consideration window size is given by the window radius. An instance of `otb::SurfaceAdjacencyEffect6SCorrectionSchemeFilter` is created.

```
typedef otb::SurfaceAdjacencyEffect6SCorrectionSchemeFilter<ImageType,
    ImageType>
SurfaceAdjacencyEffect6SCorrectionSchemeFilterType;
SurfaceAdjacencyEffect6SCorrectionSchemeFilterType::Pointer
  filterSurfaceAdjacencyEffect6SCorrectionSchemeFilter
  = SurfaceAdjacencyEffect6SCorrectionSchemeFilterType::New();
```

The needs four input informations:

- Radiometric informations (the output of the AtmosphericCorrectionParameterTo6SRadiativeTerms filter);
- The zenithal viewing angle;
- The neighborhood window radius;
- The pixel spacing in kilometers.

At this step, each filter of the chain is instancied and every one has its input paramters set. A name can be given to the output image and each filter can linked to other to create the final processing chain.

```
writer->SetFileName(argv[2]);

filterImageToLuminance->SetInput(reader->GetOutput());
filterLuminanceToReflectance->SetInput(filterImageToLuminance->GetOutput());
filterReflectanceToSurfaceReflectanceImageFilter->SetInput(
  filterLuminanceToReflectance->GetOutput());
filterSurfaceAdjacencyEffect6SCorrectionSchemeFilter->SetInput(
  filterReflectanceToSurfaceReflectanceImageFilter->GetOutput());

writer->SetInput(
  filterSurfaceAdjacencyEffect6SCorrectionSchemeFilter->GetOutput());
```

The invocation of the `Update()` method on the writer triggers the execution of the pipeline. It is recommended to place this call in a `try/catch` block in case errors occur and exceptions are thrown.

```
try
  {
  writer->Update();
```

```
  }
catch (itk::ExceptionObject& excep)
  {
  std::cerr << "Exception caught !" << std::endl;
  std::cerr << excep << std::endl;
  }
```

CHAPTER

THIRTEEN

IMAGE FUSION

Satellite sensors present an important diversity in terms of characteristics. Some provide a high spatial resolution while other focus on providing several spectral bands. The fusion process brings the information from different sensors with different characteristics together to get the best of both worlds.

Most of the fusion methods in the remote sensing community deal with the *pansharpening technique*. This fusion combines the image from the PANchromatic sensor of one satellite (high spatial resolution data) with the multispectral (XS) data (lower resolution in several spectral bands) to generate images with a high resolution and several spectral bands. Several advantages make this situation easier:

- PAN and XS images are taken simultaneously from the same satellite (or with a very short delay);
- the imaged area is common to both scenes;
- many satellites provide these data (SPOT 1-5, Quickbird, Pleiades)

This case is well-studied in the literature and many methods exist. Only very few are available in OTB now but this should evolve soon.

13.1 Simple Pan Sharpening

A simple way to view the pan-sharpening of data is to consider that, at the same resolution, the panchromatic channel is the sum of the XS channel. After putting the two images in the same geometry, after orthorectification (see chapter 11) with an oversampling of the XS image, we can proceed to the data fusion.

The idea is to apply a low pass filter to the panchromatic band to give it a spectral content (in the

Fourier domain) equivalent to the XS data. Then we normalize the XS data with this low-pass panchromatic and multiply the result with the original panchromatic band.

The process is described on figure 13.1.

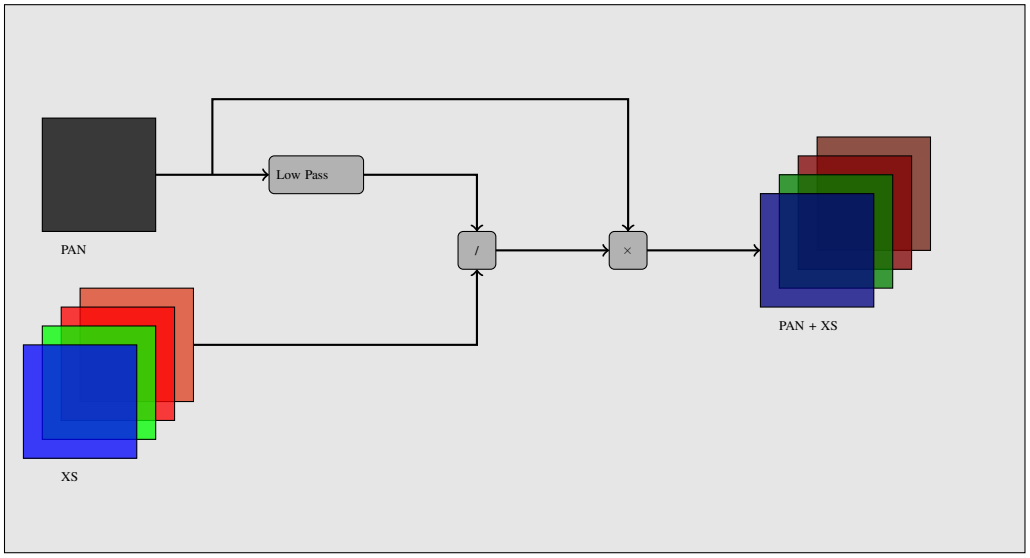


Figure 13.1: Simple pan-sharpening procedure.

The source code for this example can be found in the file `Examples/Fusion/PanSharpeningExample.cxx`.

Here we are illustrating the use of the `otb::SimpleRcsPanSharpeningFusionImageFilter` for PAN-sharpening. This example takes a PAN and the corresponding XS images as input. These images are supposed to be registered.

The fusion operation is defined as

$$\frac{XS}{\text{Filtered}(PAN)}PAN \tag{13.1}$$

Figure 13.2 shows the result of applying this PAN sharpening filter to a Quickbird image.

We start by including the required header and declaring the main function:

```
#include "otbImage.h"
#include "otbVectorImage.h"
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
#include "otbSimpleRcsPanSharpeningFusionImageFilter.h"
```

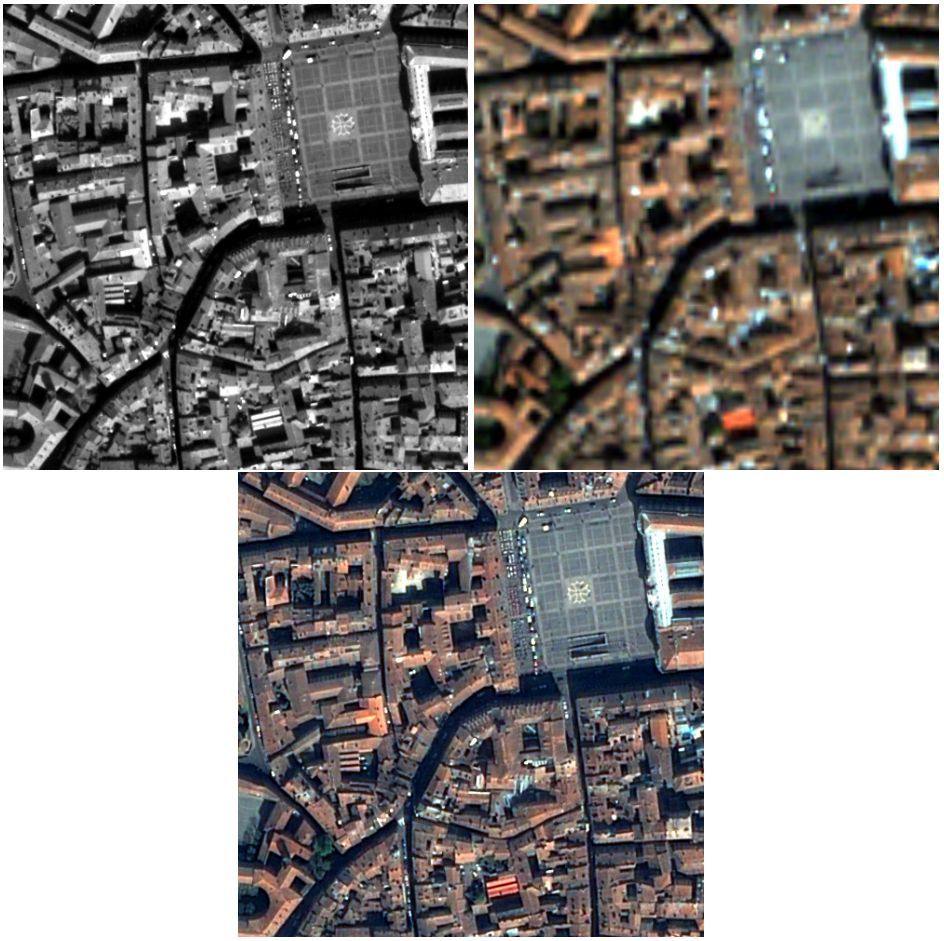


Figure 13.2: Result of applying the `otb::SimpleRcsPanSharpeningFusionImageFilter` to orthorectified Quickbird image. From left to right : original PAN image, original XS image and the result of the PAN sharpening

```
int main(int argc, char* argv[])
{
```

We declare the different image type used here as well as the image reader. Note that, the reader for the PAN image is templated by an `otb::Image` while the XS reader uses an `otb::VectorImage`.

```
  typedef otb::Image<double, 2>                    ImageType;
  typedef otb::VectorImage<double, 2>              VectorImageType;
  typedef otb::ImageFileReader<ImageType>          ReaderType;
  typedef otb::ImageFileReader<VectorImageType>    ReaderVectorType;
  typedef otb::VectorImage<unsigned short int, 2> VectorIntImageType;

  ReaderVectorType::Pointer readerXS = ReaderVectorType::New();
  ReaderType::Pointer       readerPAN = ReaderType::New();
```

We pass the filenames to the readers

```
  readerPAN->SetFileName(argv[1]);
  readerXS->SetFileName(argv[2]);
```

We declare the fusion filter an set its inputs using the readers:

```
  typedef otb::SimpleRcsPanSharpeningFusionImageFilter
  <ImageType, VectorImageType, VectorIntImageType> FusionFilterType;
  FusionFilterType::Pointer fusion = FusionFilterType::New();
  fusion->SetPanInput(readerPAN->GetOutput());
  fusion->SetXsInput(readerXS->GetOutput());
```

And finally, we declare the writer and call its `Update()` method to trigger the full pipeline execution.

```
  typedef otb::ImageFileWriter<VectorIntImageType> WriterType;
  WriterType::Pointer writer = WriterType::New();
  writer->SetFileName(argv[3]);
  writer->SetInput(fusion->GetOutput());
  writer->Update();
```

13.2 Bayesian Data Fusion

The source code for this example can be found in the file `Examples/Fusion/BayesianFusionImageFilter.cxx`.

The following example illustrates the use of the `otb::BayesianFusionFilter`. The Bayesian data fusion relies on the idea that variables of interest, denoted as vector $\mathbf{Z}$, cannot be directly observed. They are linked to the observable variables $\mathbf{Y}$ through the following error-like model.

$$\mathbf{Y} = g(\mathbf{Z}) + \mathbf{E} \tag{13.2}$$

where g(**Z**) is a set of functionals and **E** is a vector of random errors that are stochastically independent from **Z**. This algorithm uses elementary probability calculus, and several assumptions to compute the data fusion. For more explication see Fasbender, Radoux and Bogaert's publication [41]. Three images are used :

- a panchromatic image,
- a multispectral image resampled at the panchromatic image spatial resolution,
- a multispectral image resampled at the panchromatic image spatial resolution, using, e.g. a cubic interpolator.
- a float : λ, the meaning of the weight to be given to the panchromatic image compared to the multispectral one.

Let's look at the minimal code required to use this algorithm. First, the following header defining the otb::BayesianFusionFilter class must be included.

```
#include "otbBayesianFusionFilter.h"
```

The image types are now defined using pixel types and particular dimension. The panchromatic image is defined as an `otb::Image` and the multispectral one as `otb::VectorImage`.

```
typedef double InternalPixelType;
const unsigned int Dimension = 2;
typedef otb::Image<InternalPixelType, Dimension>       PanchroImageType;
typedef otb::VectorImage<InternalPixelType, Dimension> MultiSpecImageType;
```

The Bayesian data fusion filter type is instantiated using the images types as a template parameters.

```
typedef otb::BayesianFusionFilter<MultiSpecImageType,
    MultiSpecImageType,
    PanchroImageType,
    OutputImageType>
BayesianFusionFilterType;
```

Next the filter is created by invoking the `New()` method and assigning the result to a `itk::SmartPointer`.

```
BayesianFusionFilterType::Pointer bayesianFilter =
  BayesianFusionFilterType::New();
```

Now the multi spectral image, the interpolated multi spectral image and the panchromatic image are given as inputs to the filter.

```
bayesianFilter->SetMultiSpect(multiSpectReader->GetOutput());
bayesianFilter->SetMultiSpectInterp(multiSpectInterpReader->GetOutput());
bayesianFilter->SetPanchro(panchroReader->GetOutput());

writer->SetInput(bayesianFilter->GetOutput());
```

Figure 13.3: Input images used for this example (©European Space Imaging).

The BayesianFusionFilter requires defining one parameter : λ. The λ parameter can be used to tune the fusion toward either a high color consistency or sharp details. Typical λ value range in $[0.5, 1[$, where higher values yield sharper details. by default λ is set at 0.9999.

```
bayesianFilter->SetLambda(atof(argv[9]));
```

The invocation of the `Update()` method on the writer triggers the execution of the pipeline. It is recommended to place update calls in a `try/catch` block in case errors occur and exceptions are thrown.

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& excep)
  {
  std::cerr << "Exception caught !" << std::endl;
  std::cerr << excep << std::endl;
  }
```

Let's now run this example using as input the images `multiSpect.tif` , `multiSpectInterp.tif` and `panchro.tif` provided in the directory `Examples/Data`. The results obtained for 2 different values for λ are shown in figure 13.3.

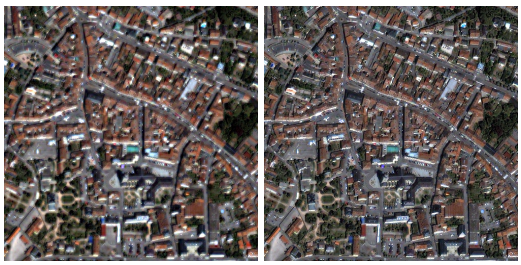


Figure 13.4: Fusion results for the Bayesian Data Fusion filter for $\lambda = 0.5$ on the left and $\lambda = 0.9999$ on the right.

CHAPTER

FOURTEEN

FEATURE EXTRACTION

Under the term *Feature Extraction* we include several techniques aiming to detect or extract informations of low level of abstraction from images. These *features* can be objects : points, lines, etc. They can also be measures : moments, textures, etc.

14.1 Textures

14.1.1 Haralick Descriptors

This example illustrates the use of the `otb::ScalarImageToTexturesFilter`, which compute the standard Haralick's textural features [56] presented in table 14.1.1, where μ_t and σ_t are the mean and standard deviation of the row (or column, due to symmetry) sums, $\mu =$ (weighted pixel average) $= \sum_{i,j} i \cdot g(i,j) = \sum_{i,j} j \cdot g(i,j)$ due to matrix summetry, and $\sigma =$ (weighted pixel variance) $= \sum_{i,j} (i-\mu)^2 \cdot g(i,j) = \sum_{i,j} (j-\mu)^2 \cdot g(i,j)$ due to matrix symmetry.

More features are available in `otb::ScalarImageToAdvancedTexturesFilter`. **The following classes provide similar functionality:**

- `otb::ScalarImageToAdvancedTexturesFilter`
- `otb::ScalarImageToPanTexTextureFilter`
- `otb::MaskedScalarImageToGreyLevelCooccurrenceMatrixGenerator`
- `itk::GreyLevelCooccurrenceMatrixTextureCoefficientsCalculator`
- `otb::GreyLevelCooccurrenceMatrixAdvancedTextureCoefficientsCalculator`

The source code for this example can be found in the file
`Examples/FeatureExtraction/TextureExample.cxx`.

The first step required to use the filter is to include the header file.

Energy	$f_1 = \sum_{i,j} g(i,j)^2$
Entropy	$f_2 = -\sum_{i,j} g(i,j) \log_2 g(i,j)$, or 0 if $g(i,j) = 0$
Correlation	$f_3 = \sum_{i,j} \frac{(i-\mu)(j-\mu)g(i,j)}{\sigma^2}$
Difference Moment	$f_4 = \sum_{i,j} \frac{1}{1+(i-j)^2} g(i,j)$
Inertia (a.k.a. Contrast)	$f_5 = \sum_{i,j} (i-j)^2 g(i,j)$
Cluster Shade	$f_6 = \sum_{i,j} ((i-\mu)+(j-\mu))^3 g(i,j)$
Cluster Prominence	$f_7 = \sum_{i,j} ((i-\mu)+(j-\mu))^4 g(i,j)$
Haralick's Correlation	$f_8 = \frac{\sum_{i,j}(i,j)g(i,j) - \mu_t^2}{\sigma_t^2}$

Table 14.1: Haralick features [56] available in `otb::ScalarImageToTexturesFilter`

```
#include "otbScalarImageToTexturesFilter.h"
```

After defining the types for the pixels and the images used in the example, we define the types for the textures filter. It is templated by the input and output image types.

```
typedef otb::ScalarImageToTexturesFilter
<ImageType, ImageType> TexturesFilterType;
```

We can now instantiate the filters.

```
TexturesFilterType::Pointer texturesFilter
  = TexturesFilterType::New();
```

The texture filters takes at least 2 parameters: the radius of the neighborhood on which the texture will be computed and the offset used. Texture features are bivariate statistics, that is, they are computed using pair of pixels. Each texture feature is defined for an offset defining the pixel pair.

The radius parameter can be passed to the filter as a scalar parameter if the neighborhood is square, or as `SizeType` in any case.

The offset is always an array of N values, where N is the number of dimensions of the image.

```
typedef ImageType::SizeType SizeType;
SizeType sradius;
sradius.Fill(radius);

texturesFilter->SetRadius(sradius);

typedef ImageType::OffsetType OffsetType;
OffsetType offset;
offset[0] =  xOffset;
offset[1] =  yOffset;

texturesFilter->SetOffset(offset);
```

The textures filter will automatically derive the optimal bin size for co-occurences histogram, but they need to know the input image minimum and maximum. These values can be set like this :

```
texturesFilter->SetInputImageMinimum(0);
texturesFilter->SetInputImageMaximum(255);
```

To tune co-occurence histogram resolution, you can use the SetNumberOfBinsPerAxis() method.

We can now plug the pipeline.

```
texturesFilter->SetInput(reader->GetOutput());

writer->SetInput(texturesFilter->GetInertiaOutput());
writer->Update();
```

Figure 14.1 shows the result of applying the contrast texture computation.

Figure 14.1: Result of applying the `otb::ScalarImageToTexturesFilter` to an image. From left to right : original image, contrast.

14.1.2 PanTex

The source code for this example can be found in the file `Examples/FeatureExtraction/PanTexExample.cxx`.

This example illustrates the use of the `otb::ScalarImageToPanTexTextureFilter`. This texture parameter was first introduced in [107] and is very useful for urban area detection. **The following classes provide similar functionality:**

- `otb::ScalarImageToTexturesFilter`
- `otb::ScalarImageToAdvancedTexturesFilter`

The first step required to use this filter is to include its header file.

```
#include "otbScalarImageToPanTexTextureFilter.h"
```

After defining the types for the pixels and the images used in the example, we define the type for the PanTex filter. It is templated by the input and output image types.

```
typedef otb::ScalarImageToPanTexTextureFilter
<ImageType, ImageType> PanTexTextureFilterType;
```

We can now instatiate the filter.

```
PanTexTextureFilterType::Pointer textureFilter = PanTexTextureFilterType::New();
```

Figure 14.2: Result of applying the `otb::ScalarImageToPanTexTextureFilter` to an image. From left to right: original image, PanTex feature.

Then, we set the parameters of the filter.The radius of the neighborhood to compute the texture. The number of bins per axis for histogram generation (it is the size of the co-occurrence matrix). Moreover, we have to specify the Min/Max in the input image. In the example, image Min/Max is set by the user to 0 and 255. Alternatively you can use the class `itk::MinimumMaximumImageCalculator` to calculate these values.

```
PanTexTextureFilterType::SizeType sradius;
sradius.Fill(4);
textureFilter->SetNumberOfBinsPerAxis(8);
textureFilter->SetRadius(sradius);
textureFilter->SetInputImageMinimum(0);
textureFilter->SetInputImageMaximum(255);
```

We can now plug the pipeline and trigger the execution by calling the `Update` method of the writer.

```
textureFilter->SetInput(reader->GetOutput());
writer->SetInput(textureFilter->GetOutput());

writer->Update();
```

Figure 14.2 shows the result of applying the PanTex computation.

14.1.3 Structural Feature Set

The source code for this example can be found in the file
`Examples/FeatureExtraction/SFSExample.cxx`.

This example illustrates the use of the `otb::SFSTexturesImageFilter`. This filter computes the Structural Feature Set as descibed in [61]. These features are textural parameters which give information about the structure of lines passing through each pixel of the image.

The first step required to use this filter is to include its header file.

```
#include "otbSFSTexturesImageFilter.h"
```

As with every OTB program, we start by defining the types for the images, the readers and the writers.

```
typedef otb::Image<PixelType, Dimension> ImageType;
typedef otb::ImageFileReader<ImageType>  ReaderType;
typedef otb::ImageFileWriter<ImageType>  WriterType;
```

The we can instantiate the type for the SFS filter, which is templated over the input and output pixel types.

```
typedef otb::SFSTexturesImageFilter<ImageType, ImageType> SFSFilterType;
```

After that, we can instantiate the filter. We will also instantiate the reader and one writer for each output image, since the SFS filter generates 6 different features.

```
SFSFilterType::Pointer filter    = SFSFilterType::New();
ReaderType::Pointer    reader       = ReaderType::New();
WriterType::Pointer    writerLength = WriterType::New();
WriterType::Pointer    writerWidth  = WriterType::New();
WriterType::Pointer    writerWMean  = WriterType::New();
WriterType::Pointer    writerRatio  = WriterType::New();
WriterType::Pointer    writerSD     = WriterType::New();
WriterType::Pointer    writerPsi    = WriterType::New();
```

The SFS filter has several parameters which have to be selected. They are:

1. a spectral threshold to decide if 2 neighboring pixels are connected;
2. a spatial threshold defining the maximum length for an extracted line;
3. the number of directions which will be analyzed (the first one is to the right and they are equally distributed between 0 and 2π);
4. the α parameter fort the $\omega - mean$ feature;
5. the RatioMax parameter fort the $\omega - mean$ feature.

```
filter->SetSpectralThreshold(spectThresh);
filter->SetSpatialThreshold(spatialThresh);
filter->SetNumberOfDirections(dirNb);
filter->SetRatioMaxConsiderationNumber(maxConsideration);
filter->SetAlpha(alpha);
```

In order to disable the computation of a feature, the `SetFeatureStatus` parameter can be used. The *true* value enables the feature (default behavior) and the $false$ value disables the computation. Therefore, the following line is useless, but is given here as an example.

```
filter->SetFeatureStatus(SFSFilterType::PSI, true);
```

Now, we plug the pipeline using all the writers.

```
filter->SetInput(reader->GetOutput());

writerLength->SetFileName(outNameLength);
writerLength->SetInput(filter->GetLengthOutput());
writerLength->Update();

writerWidth->SetFileName(outNameWidth);
writerWidth->SetInput(filter->GetWidthOutput());
writerWidth->Update();

writerWMean->SetFileName(outNameWMean);
writerWMean->SetInput(filter->GetWMeanOutput());
writerWMean->Update();

writerRatio->SetFileName(outNameRatio);
writerRatio->SetInput(filter->GetRatioOutput());
writerRatio->Update();

writerSD->SetFileName(outNameSD);
writerSD->SetInput(filter->GetSDOutput());
writerSD->Update();

writerPsi->SetFileName(outNamePsi);
writerPsi->SetInput(filter->GetPSIOutput());
writerPsi->Update();
```

Figure 14.3 shows the result of applying the SFS computation to an image

14.2 Interest Points

14.2.1 Harris detector

The source code for this example can be found in the file `Examples/FeatureExtraction/HarrisExample.cxx`.

This example illustrates the use of the `otb::HarrisImageFilter`.

The first step required to use this filter is to include its header file.

```
#include "otbHarrisImageFilter.h"
```

The `otb::HarrisImageFilter` is templated over the input and output image types, so we start by defining:

```
typedef otb::HarrisImageFilter<InputImageType,
    InputImageType>   HarrisFilterType;
```

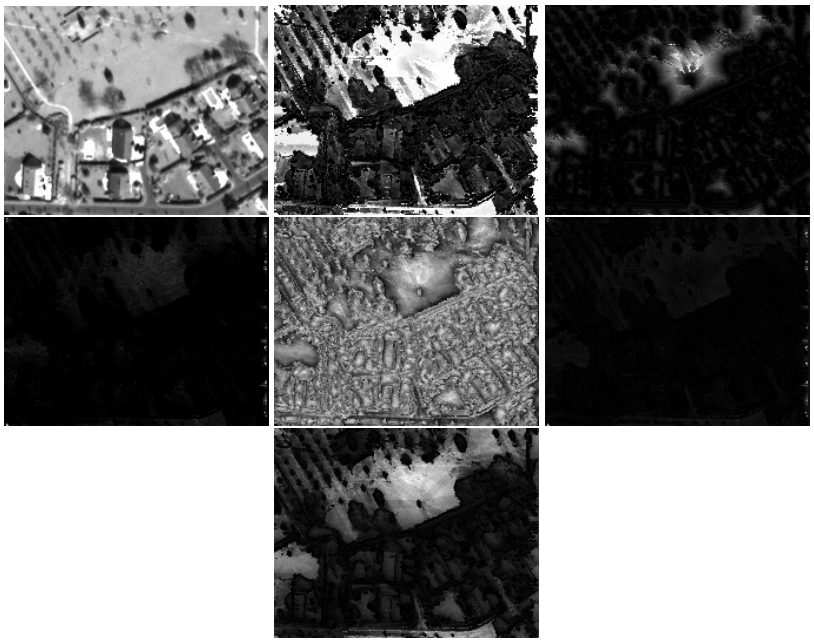


Figure 14.3: Result of applying the `otb::SFSTexturesImageFilter` to an image. From left to right and top to bottom: original image, length, width, ω-mean, ratio, SD and Psi structural features. original image, .

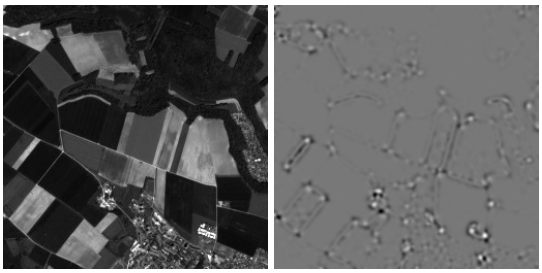


Figure 14.4: Result of applying the `otb::HarrisImageFilter` to a Spot 5 image.

The `otb::HarrisImageFilter` needs some parameters to operate. The derivative computation is performed by a convolution with the derivative of a Gaussian kernel of variance σ_D (derivation scale) and the smoothing of the image is performed by convolving with a Gaussian kernel of variance σ_I (integration scale). This allows the computation of the following matrix:

$$\mu(\mathbf{x},\sigma_I,\sigma_D) = \sigma_D^2 g(\sigma_I) \star \begin{bmatrix} L_x^2(\mathbf{x},\sigma_D) & L_xL_y(\mathbf{x},\sigma_D) \\ L_xL_y(\mathbf{x},\sigma_D) & L_y^2(\mathbf{x},\sigma_D) \end{bmatrix} \tag{14.1}$$

The output of the detector is

$$det(\mu) - \alpha trace^2(\mu).$$

```
harris->SetSigmaD(SigmaD);
harris->SetSigmaI(SigmaI);
harris->SetAlpha(Alpha);
```

Figure 14.4 shows the result of applying the interest point detector to a small patch extracted from a Spot 5 image.

The output of the `otb::HarrisImageFilter` is an image where, for each pixel, we obtain the intensity of the detection. Often, the user may want to get access to the set of points for which the output of the detector is higher than a given threshold. This can be obtained by using the `otb::HarrisImageToPointSetFilter`. This filter is only templated over the input image type, the output being a `itk::PointSet` with pixel type equal to the image pixel type.

```
typedef otb::HarrisImageToPointSetFilter<InputImageType> FunctionType;
```

We declare now the filter and a pointer to the output point set.

```
typedef FunctionType::OutputPointSetType OutputPointSetType;

FunctionType::Pointer       harrisPoints    = FunctionType::New();
OutputPointSetType::Pointer pointSet = OutputPointSetType::New();
```

The `otb::HarrisImageToPointSetFilter` takes the same parameters as the `otb::HarrisImageFilter` and an additional parameter : the threshold for the point selection.

```
harrisPoints->SetInput(0, reader->GetOutput());
harrisPoints->SetSigmaD(SigmaD);
harrisPoints->SetSigmaI(SigmaI);
harrisPoints->SetAlpha(Alpha);
harrisPoints->SetLowerThreshold(10);
pointSet = harrisPoints->GetOutput();
```

We can now iterate through the obtained pointset and access the coordinates of the points. We start by accessing the container of the points which is encapsulated into the point set (see section 5.2 for more information on using `itk::PointSet`s) and declaring an iterator to it.

```
typedef OutputPointSetType::PointsContainer ContainerType;
ContainerType* pointsContainer = pointSet->GetPoints();
typedef ContainerType::Iterator IteratorType;
IteratorType itList = pointsContainer->Begin();
```

And we get the points coordinates

```
while (itList != pointsContainer->End())
  {
  typedef OutputPointSetType::PointType OutputPointType;
  OutputPointType pCoordinate = (itList.Value());
  std::cout << pCoordinate << std::endl;
  ++itList;
  }
```

14.2.2 SIFT detector

14.2.3 SURF detector

The source code for this example can be found in the file
`Examples/FeatureExtraction/SURFExample.cxx`.

This example illustrates the use of the `otb::ImageToSURFKeyPointSetFilter`. The Speed-Up Robust Features (or SURF) is an algorithm in computer vision to detect and describe local features in images. The algorithm is detailed in [10]. The applications of SURF are the same as those for SIFT.

The first step required to use this filter is to include its header file.

```
#include "otbImageToSURFKeyPointSetFilter.h"
```

We will start by defining the required types. We will work with a scalar image of float pixels. We also define the corresponding image reader.

```
typedef float                           RealType;
typedef otb::Image<RealType, Dimension> ImageType;
typedef otb::ImageFileReader<ImageType> ReaderType;
```

The SURF descriptors will be stored in a point set containing the vector of features.

```
typedef itk::VariableLengthVector<RealType>      RealVectorType;
typedef itk::PointSet<RealVectorType, Dimension> PointSetType;
```

The SURF filter itself is templated over the input image and the generated point set.

```
typedef otb::ImageToSURFKeyPointSetFilter<ImageType, PointSetType>
ImageToFastSURFKeyPointSetFilterType;
```

We instantiate the reader.

```
ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(infname);
```

We instantiate the filter.

```
ImageToFastSURFKeyPointSetFilterType::Pointer filter =
  ImageToFastSURFKeyPointSetFilterType::New();
```

We plug the filter and set the number of scales for the SURF computation. We can afterwards run the processing with the `Update()` method.

```
filter->SetInput(reader->GetOutput());
filter->SetOctavesNumber(octaves);
filter->SetScalesNumber(scales);
filter->Update();
```

Once the SURF are computed, we may want to draw them on top of the input image. In order to do this, we will create the following RGB image and the corresponding writer:

```
typedef unsigned char                          PixelType;
typedef itk::RGBPixel<PixelType>               RGBPixelType;
typedef otb::Image<RGBPixelType, 2>            OutputImageType;
typedef otb::ImageFileWriter<OutputImageType> WriterType;

OutputImageType::Pointer outputImage = OutputImageType::New();
```

We set the regions of the image by copying the information from the input image and we allocate the memory for the output image.

```
outputImage->SetRegions(reader->GetOutput()->GetLargestPossibleRegion());
outputImage->Allocate();
```

We can now proceed to copy the input image into the output one using region iterators. The input image is a grey level one. The output image will be made of color crosses for each SURF on top of the grey level input image. So we start by copying the grey level values on each of the 3 channels of the color image.

```
itk::ImageRegionIterator<OutputImageType> iterOutput(
  outputImage,
  outputImage->
  GetLargestPossibleRegion());
itk::ImageRegionIterator<ImageType> iterInput(reader->GetOutput(),
                                              reader->GetOutput()->
                                              GetLargestPossibleRegion());

for (iterOutput.GoToBegin(), iterInput.GoToBegin();
     !iterOutput.IsAtEnd();
     ++iterOutput, ++iterInput)
  {
  OutputImageType::PixelType rgbPixel;
  rgbPixel.SetRed(static_cast<PixelType>(iterInput.Get()));
  rgbPixel.SetGreen(static_cast<PixelType>(iterInput.Get()));
  rgbPixel.SetBlue(static_cast<PixelType>(iterInput.Get()));

  iterOutput.Set(rgbPixel);
  }
```

We are now going to plot color crosses on the output image. We will need to define offsets (top, bottom, left and right) with respect to the SURF position in order to draw the cross segments.

```
ImageType::OffsetType t = {{ 0, 1}};
ImageType::OffsetType b = {{ 0, -1}};
ImageType::OffsetType l = {{ 1, 0}};
ImageType::OffsetType r = {{-1, 0}};
```

Now, we are going to access the point set generated by the SURF filter. The points are stored into a points container that we are going to walk through using an iterator. These are the types needed for this task:

```
typedef PointSetType::PointsContainer PointsContainerType;
typedef PointsContainerType::Iterator PointsIteratorType;
```

We set the iterator to the beginning of the point set.

```
PointsIteratorType pIt = filter->GetOutput()->GetPoints()->Begin();
```

We get the information about image size and spacing before drawing the crosses.

```
ImageType::SpacingType spacing = reader->GetOutput()->GetSpacing();
ImageType::PointType origin = reader->GetOutput()->GetOrigin();
//OutputImageType::SizeType size = outputImage->GetLargestPossibleRegion().GetSize();
```

And we iterate through the SURF set:

```
while (pIt != filter->GetOutput()->GetPoints()->End())
  {
```

We get the pixel coordinates for each SURF by using the `Value()` method on the point set iterator. We use the information about size and spacing in order to convert the physical coordinates of the point into pixel coordinates.

```
ImageType::IndexType index;

index[0] = static_cast<unsigned int>(vcl_floor(
                                        static_cast<double>(
                                          (pIt.Value()[0] -
                                           origin[0]) / spacing[0] + 0.5
                                          )));

index[1] = static_cast<unsigned int>(vcl_floor(
                                        static_cast<double>(
                                          (pIt.Value()[1] -
                                           origin[1]) / spacing[1] + 0.5
                                          )));
```

We create a green pixel.

```
OutputImageType::PixelType keyPixel;
keyPixel.SetRed(0);
keyPixel.SetGreen(255);
keyPixel.SetBlue(0);
```

We draw the crosses using the offsets and checking that we are inside the image, since SURFs on the image borders would cause an out of bounds pixel access.

```
if (outputImage->GetLargestPossibleRegion().IsInside(index))
  {
  outputImage->SetPixel(index, keyPixel);

  if (outputImage->GetLargestPossibleRegion().IsInside(index +
                                                       t))
    outputImage->
    SetPixel(index + t, keyPixel);

  if (outputImage->GetLargestPossibleRegion().IsInside(index +
                                                       b))
    outputImage->
    SetPixel(index + b, keyPixel);

  if (outputImage->GetLargestPossibleRegion().IsInside(index +
                                                       l))
    outputImage->
    SetPixel(index + l, keyPixel);

  if (outputImage->GetLargestPossibleRegion().IsInside(index +
                                                       r))
    outputImage->
    SetPixel(index + r, keyPixel);
  }
++pIt;
```

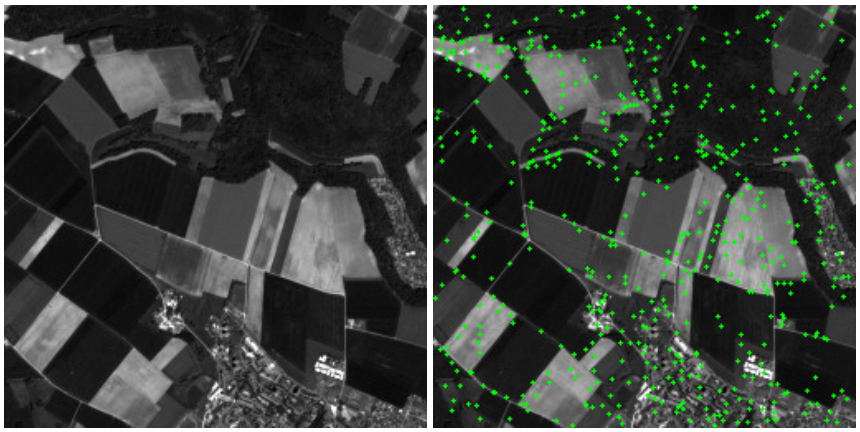


Figure 14.5: Result of applying the `otb::ImageToSURFKeyPointSetFilter` to a Spot 5 image.

```
}
```

Finally, we write the image.

```
WriterType::Pointer writer = WriterType::New();
writer->SetFileName(outputImageFilename);
writer->SetInput(outputImage);
writer->Update();
```

Figure 14.5 shows the result of applying the SURF point detector to a small patch extracted from a Spot 5 image.

14.3 Alignments

The source code for this example can be found in the file
`Examples/FeatureExtraction/AlignmentsExample.cxx`.

This example illustrates the use of the `otb::ImageToPathListAlignFilter`. This filter allows to extract meaninful alignments. Alignments (that is edges and lines) are detected using the *Gestalt* approach proposed by Desolneux et al. [39]. In this context, an event is considered meaningful if the expectation of its occurrence would be very small in a random image. One can thus consider that in a random image the direction of the gradient of a given point is uniformly distributed, and that neighbouring pixels have a very low probability of having the same gradient direction. This algorithm gives a set of straight line segments defined by the two extremity coordinates under the form of a `std::list` of `itk::PolyLineParametricPath`.

The first step required to use this filter is to include its header.

```
#include "otbImageToPathListAlignFilter.h"
```

In order to visualize the detected alignments, we will use the facility class `otb::DrawPathFilter` which draws a `itk::PolyLineParametricPath` on top of a given image.

```
#include "itkPolyLineParametricPath.h"
#include "otbDrawPathFilter.h"
```

The `otb::ImageToPathListAlignFilter` is templated over the input image type and the output path type, so we start by defining:

```
typedef itk::PolyLineParametricPath<Dimension> PathType;
typedef otb::ImageToPathListAlignFilter<InputImageType, PathType>
ListAlignFilterType;
```

Next, we build the pipeline.

```
ListAlignFilterType::Pointer alignFilter = ListAlignFilterType::New();

alignFilter->SetInput(reader->GetOutput());
```

We can choose the number of accepted false alarms in the detection with the method `SetEps()` for which the parameter is of the form $-log10(\text{max. number of false alarms})$.

```
alignFilter->SetEps(atoi(argv[3]));
```

As stated, above, the `otb::DrawPathFilter`, is useful for drawint the detected alignments. This class is templated over the input image and path types and also on the output image type.

```
typedef otb::DrawPathFilter<InputImageType, PathType,
    OutputImageType>  DrawPathFilterType;
```

We will now go through the list of detected paths and feed them to the `otb::DrawPathFilter` inside a loop. We will use a list iterator inside a `while` statement.

```
typedef ListAlignFilterType::OutputPathListType ListType;

ListType* pathList = alignFilter->GetOutput();

ListType::Iterator listIt = pathList->Begin();
```

We define a dummy image will be iteratively fed to the `otb::DrawPathFilter` after the drawing of each alignment.

```
InputImageType::Pointer backgroundImage = reader->GetOutput();
```

We iterate through the list and write the result to a file.

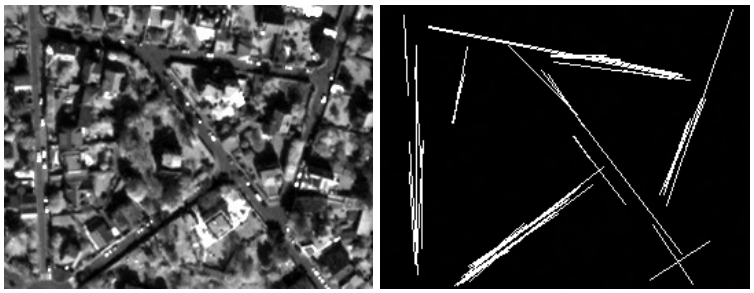


Figure 14.6: Result of applying the `otb::ImageToPathListAlignFilter` to a VHR image of a suburb.

```
while (listIt != pathList->End())
  {

  DrawPathFilterType::Pointer drawPathFilter = DrawPathFilterType::New();
  drawPathFilter->SetImageInput(backgroundImage);
  drawPathFilter->SetInputPath(listIt.Get());

  drawPathFilter->SetValue(itk::NumericTraits<OutputPixelType>::max());
  drawPathFilter->Update();

  backgroundImage = drawPathFilter->GetOutput();

  ++listIt;

  }

writer->SetInput(backgroundImage);
```

Figure 14.6 shows the result of applying the alignment detection to a small patch extracted from a VHR image.

14.4 Lines

14.4.1 Line Detection

The source code for this example can be found in the file
`Examples/FeatureExtraction/RatioLineDetectorExample.cxx`.

This example illustrates the use of the `otb::RatioLineDetectorImageFilter`. This filter is used for line detection in SAR images. Its principle is described in [131]: a line is detected if two parallel edges are present in the images. These edges are detected with the ratio of means detector.

The first step required to use this filter is to include its header file.

```
#include "otbLineRatioDetectorImageFilter.h"
```

Then we must decide what pixel type to use for the image. We choose to make all computations with floating point precision and rescale the results between 0 and 255 in order to export PNG images.

```
typedef  float         InternalPixelType;
typedef  unsigned char OutputPixelType;
```

The images are defined using the pixel type and the dimension.

```
typedef otb::Image<InternalPixelType,  2> InternalImageType;
typedef otb::Image<OutputPixelType,  2>   OutputImageType;
```

The filter can be instantiated using the image types defined above.

```
typedef otb::LineRatioDetectorImageFilter
<InternalImageType, InternalImageType>  FilterType;
```

An `otb::ImageFileReader` class is also instantiated in order to read image data from a file.

```
typedef otb::ImageFileReader<InternalImageType> ReaderType;
```

An `otb::ImageFileWriter` is instantiated in order to write the output image to a file.

```
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

The intensity rescaling of the results will be carried out by the `itk::RescaleIntensityImageFilter` which is templated by the input and output image types.

```
typedef itk::RescaleIntensityImageFilter<InternalImageType,
    OutputImageType> RescalerType;
```

Both the filter and the reader are created by invoking their `New()` methods and assigning the result to SmartPointers.

```
ReaderType::Pointer reader = ReaderType::New();
FilterType::Pointer filter = FilterType::New();
```

The same is done for the rescaler and the writer.

```
RescalerType::Pointer rescaler = RescalerType::New();
WriterType::Pointer   writer = WriterType::New();
```

The `itk::RescaleIntensityImageFilter` needs to know which is the minimu and maximum values of the output generated image. Those can be chosen in a generic way by using the `NumericTraits` functions, since they are templated over the pixel type.

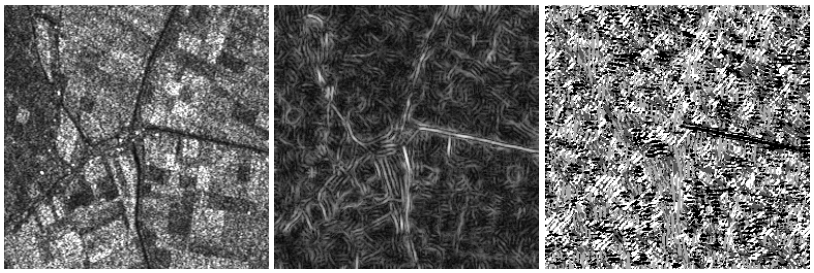


Figure 14.7: Result of applying the `otb::LineRatioDetectorImageFilter` to a SAR image. From left to right : original image, line intensity and edge orientation.

```
rescaler->SetOutputMinimum(itk::NumericTraits<OutputPixelType>::min());
rescaler->SetOutputMaximum(itk::NumericTraits<OutputPixelType>::max());
```

The image obtained with the reader is passed as input to the `otb::LineRatioDetectorImageFilter`. The pipeline is built as follows.

```
filter->SetInput(reader->GetOutput());
rescaler->SetInput(filter->GetOutput());
writer->SetInput(rescaler->GetOutput());
```

The methods `SetLengthLine()` and `SetWidthLine()` allow to set the minimum length and the typical witdh of the lines which are to be detected.

```
filter->SetLengthLine(atoi(argv[4]));
filter->SetWidthLine(atoi(argv[5]));
```

The filter is executed by invoking the `Update()` method. If the filter is part of a larger image processing pipeline, calling `Update()` on a downstream filter will also trigger update of this filter.

```
filter->Update();
```

We can also obtain the direction of the lines by invoking the `GetOutputDirection()` method.

```
rescaler->SetInput(filter->GetOutputDirection());
writer->SetInput(rescaler->GetOutput());
writer->Update();
```

shows the result of applying the LineRatio edge detector filter to a SAR image.

The following classes provide similar functionality:

- `otb::LineCorrelationDetectorImageFilter`

The source code for this example can be found in the file
Examples/FeatureExtraction/CorrelationLineDetectorExample.cxx.

This example illustrates the use of the otb::CorrelationLineDetectorImageFilter. This filter is used for line detection in SAR images. Its principle is described in [131]: a line is detected if two parallel edges are present in the images. These edges are detected with the correlation of means detector.

The first step required to use this filter is to include its header file.

```
#include "otbLineCorrelationDetectorImageFilter.h"
```

Then we must decide what pixel type to use for the image. We choose to make all computations with floating point precision and rescale the results between 0 and 255 in order to export PNG images.

```
typedef  float         InternalPixelType;
typedef  unsigned char OutputPixelType;
```

The images are defined using the pixel type and the dimension.

```
typedef otb::Image<InternalPixelType,  2> InternalImageType;
typedef otb::Image<OutputPixelType,  2>   OutputImageType;
```

The filter can be instantiated using the image types defined above.

```
typedef otb::LineCorrelationDetectorImageFilter<InternalImageType,
    InternalImageType>
FilterType;
```

An otb::ImageFileReader class is also instantiated in order to read image data from a file.

```
typedef otb::ImageFileReader<InternalImageType> ReaderType;
```

An otb::ImageFileWriter is instantiated in order to write the output image to a file.

```
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

The intensity rescaling of the results will be carried out by the itk::RescaleIntensityImageFilter which is templated by the input and output image types.

```
typedef itk::RescaleIntensityImageFilter<InternalImageType,
    OutputImageType> RescalerType;
```

Both the filter and the reader are created by invoking their New() methods and assigning the result to SmartPointers.

```
ReaderType::Pointer reader = ReaderType::New();
FilterType::Pointer filter = FilterType::New();
```

The same is done for the rescaler and the writer.

```
RescalerType::Pointer rescaler = RescalerType::New();
WriterType::Pointer   writer = WriterType::New();
```

The itk::RescaleIntensityImageFilter needs to know which is the minimu and maximum values of the output generated image. Those can be chosen in a generic way by using the NumericTraits functions, since they are templated over the pixel type.

```
rescaler->SetOutputMinimum(itk::NumericTraits<OutputPixelType>::min());
rescaler->SetOutputMaximum(itk::NumericTraits<OutputPixelType>::max());
```

The image obtained with the reader is passed as input to the otb::LineCorrelationDetectorImageFilter. The pipeline is built as follows.

```
filter->SetInput(reader->GetOutput());
rescaler->SetInput(filter->GetOutput());
writer->SetInput(rescaler->GetOutput());
```

The methods SetLengthLine() and SetWidthLine() allow to set the minimum length and the typical witdh of the lines which are to be detected.

```
filter->SetLengthLine(atoi(argv[4]));
filter->SetWidthLine(atoi(argv[5]));
```

The filter is executed by invoking the Update() method. If the filter is part of a larger image processing pipeline, calling Update() on a downstream filter will also trigger update of this filter.

```
filter->Update();
```

We can also obtain the direction of the lines by invoking the GetOutputDirections() method.

```
rescaler->SetInput(filter->GetOutputDirection());
writer->SetInput(rescaler->GetOutput());
writer->Update();
```

shows the result of applying the LineCorrelation edge detector filter to a SAR image.

The following classes provide similar functionality:

- otb::LineCorrelationDetectorImageFilter

The source code for this example can be found in the file Examples/FeatureExtraction/AssymmetricFusionOfLineDetectorExample.cxx.

This example illustrates the use of the otb::AssymmetricFusionOfLineDetectorImageFilter.

The first step required to use this filter is to include its header file.

```
#include "otbAssymmetricFusionOfLineDetectorImageFilter.h"
```

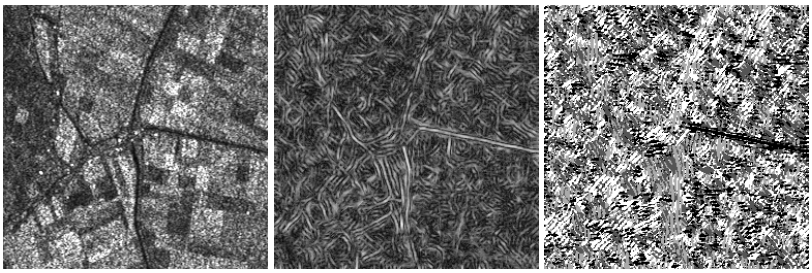


Figure 14.8: Result of applying the `otb::LineCorrelationDetectorImageFilter` to a SAR image. From left to right : original image, line intensity and edge orientation.

Then we must decide what pixel type to use for the image. We choose to make all computations with floating point precision and rescale the results between 0 and 255 in order to export PNG images.

```
typedef  float         InternalPixelType;
typedef  unsigned char OutputPixelType;
```

The images are defined using the pixel type and the dimension.

```
typedef otb::Image<InternalPixelType,  2> InternalImageType;
typedef otb::Image<OutputPixelType,  2>   OutputImageType;
```

The filter can be instantiated using the image types defined above.

```
typedef otb::AssymmetricFusionOfLineDetectorImageFilter<InternalImageType,
    InternalImageType>
FilterType;
```

An `otb::ImageFileReader` class is also instantiated in order to read image data from a file.

```
typedef otb::ImageFileReader<InternalImageType> ReaderType;
```

An `otb::ImageFileWriter` is instantiated in order to write the output image to a file.

```
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

The intensity rescaling of the results will be carried out by the `itk::RescaleIntensityImageFilter` which is templated by the input and output image types.

```
typedef itk::RescaleIntensityImageFilter<InternalImageType,
    OutputImageType> RescalerType;
```

Both the filter and the reader are created by invoking their `New()` methods and assigning the result to SmartPointers.

```
ReaderType::Pointer reader = ReaderType::New();
FilterType::Pointer filter = FilterType::New();
```

The same is done for the rescaler and the writer.

```
RescalerType::Pointer rescaler = RescalerType::New();
WriterType::Pointer   writer = WriterType::New();
```

The itk::RescaleIntensityImageFilter needs to know which is the minimu and maximum values of the output generated image. Those can be chosen in a generic way by using the NumericTraits functions, since they are templated over the pixel type.

```
rescaler->SetOutputMinimum(itk::NumericTraits<OutputPixelType>::min());
rescaler->SetOutputMaximum(itk::NumericTraits<OutputPixelType>::max());
```

The image obtained with the reader is passed as input to the otb::AssymetricFusionOfDetectorImageFilter. The pipeline is built as follows.

```
filter->SetInput(reader->GetOutput());
rescaler->SetInput(filter->GetOutput());
writer->SetInput(rescaler->GetOutput());
```

The methods SetLengthLine() and SetWidthLine() allow to set the minimum length and the typical witdh of the lines which are to be detected.

```
filter->SetLengthLine(atoi(argv[3]));
filter->SetWidthLine(atoi(argv[4]));
```

The filter is executed by invoking the Update() method. If the filter is part of a larger image processing pipeline, calling Update() on a downstream filter will also trigger update of this filter.

```
filter->Update();
```

Figure 14.9 shows the result of applying the AssymetricFusionOf edge detector filter to a SAR image.

The source code for this example can be found in the file
Examples/FeatureExtraction/ParallelLineDetectionExample.cxx.

This example illustrates the details of the otb::ParallelLinePathListFilter.

14.4.2 Segment Extraction

Local Hough Transform

The source code for this example can be found in the file
Examples/FeatureExtraction/LocalHoughExample.cxx.

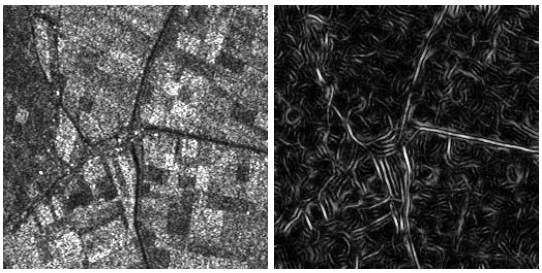


Figure 14.9: Result of applying the otb::AssymetricFusionOfDetectorImageFilter to a SAR image. From left to right : original image, line intensity.

This example illustrates the use of the otb::ExtractSegmentsImageFilter.

The first step required to use this filter is to include its header file.

```
#include "otbLocalHoughFilter.h"
#include "otbDrawLineSpatialObjectListFilter.h"
#include "otbLineSpatialObjectList.h"
```

Then we must decide what pixel type to use for the image. We choose to make all computations with floating point precision and rescale the results between 0 and 255 in order to export PNG images.

```
typedef  float          InternalPixelType;
typedef  unsigned char  OutputPixelType;
```

The images are defined using the pixel type and the dimension.

```
typedef otb::Image<InternalPixelType,  2> InternalImageType;
typedef otb::Image<OutputPixelType,  2>   OutputImageType;
```

The filter can be instantiated using the image types defined above.

```
typedef otb::LocalHoughFilter<InternalImageType> LocalHoughType;
typedef otb::DrawLineSpatialObjectListFilter<InternalImageType,
    OutputImageType>
DrawLineListType;
```

An otb::ImageFileReader class is also instantiated in order to read image data from a file.

```
typedef otb::ImageFileReader<InternalImageType> ReaderType;
```

An otb::ImageFileWriter is instantiated in order to write the output image to a file.

```
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

Both the filter and the reader are created by invoking their New() methods and assigning the result to SmartPointers.

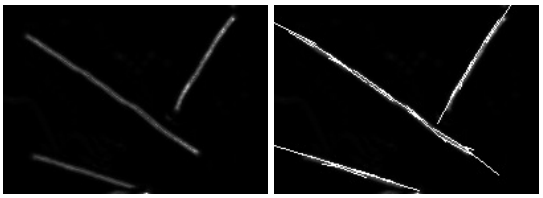


Figure 14.10: Result of applying the `otb::LocalHoughImageFilter`. From left to right : original image, extracted segments.

```
ReaderType::Pointer reader = ReaderType::New();

LocalHoughType::Pointer localHough = LocalHoughType::New();

DrawLineListType::Pointer drawLineList = DrawLineListType::New();
```

The same is done for the writer.

```
WriterType::Pointer writer = WriterType::New();
```

The image obtained with the reader is passed as input to the `otb::ExtractSegmentsImageFilter`. The pipeline is built as follows.

```
localHough->SetInput(reader->GetOutput());

drawLineList->SetInput(reader->GetOutput());
drawLineList->SetInputLineSpatialObjectList(localHough->GetOutput());
writer->SetFileName(argv[2]);
writer->SetInput(drawLineList->GetOutput());
writer->Update();
```

Figure 14.10 shows the result of applying the `otb::LocalHoughImageFilter`.

14.5 Density Features

An interesting approach to feature extraction consists in computing the density of previously detected features as simple edges or interest points.

14.5.1 Edge Density

The source code for this example can be found in the file
`Examples/FeatureExtraction/EdgeDensityExample.cxx`.

This example illustrates the use of the `otb::EdgeDensityImageFilter`. This filter computes a local density of edges on an image and can be useful to detect man made objects or urban areas, for instance. The filter has been implemented in a generic way, so that the way the edges are detected and the way their density is computed can be chosen by the user.

The first step required to use this filter is to include its header file.

```
#include "otbEdgeDensityImageFilter.h"
```

We will also include the header files for the edge detector (a Canny filter) and the density estimation (a simple count on a binary image).

The first step required to use this filter is to include its header file.

```
#include "itkCannyEdgeDetectionImageFilter.h"
#include "otbBinaryImageDensityFunction.h"
```

As usual, we start by defining the types for the images, the reader and the writer.

```
typedef otb::Image<PixelType, Dimension> ImageType;
typedef otb::ImageFileReader<ImageType>  ReaderType;
typedef otb::ImageFileWriter<ImageType>  WriterType;
```

We define now the type for the function which will be used by the edge density filter to estimate this density. Here we choose a function which counts the number of non null pixels per area. The fucntion takes as template the type of the image to be processed.

```
typedef otb::BinaryImageDensityFunction<ImageType> CountFunctionType;
```

These *non null pixels* will be the result of an edge detector. We use here the classical Canny edge detector, which is templated over the input and output image types.

```
typedef itk::CannyEdgeDetectionImageFilter<ImageType, ImageType>
CannyDetectorType;
```

Finally, we can define the type for the edge density filter which takes as template the input and output image types, the edge detector type, and the count fucntion type..

```
typedef otb::EdgeDensityImageFilter<ImageType, ImageType, CannyDetectorType,
    CountFunctionType> EdgeDensityFilterType;
```

We can now instantiate the different processing objects of the pipeline using the `New()` method.

```
ReaderType::Pointer            reader = ReaderType::New();
EdgeDensityFilterType::Pointer filter = EdgeDensityFilterType::New();
CannyDetectorType::Pointer     cannyFilter = CannyDetectorType::New();
WriterType::Pointer            writer = WriterType::New();
```

The edge detection filter needs to be instantiated because we need to set its parameters. This is what we do here for the Canny filter.

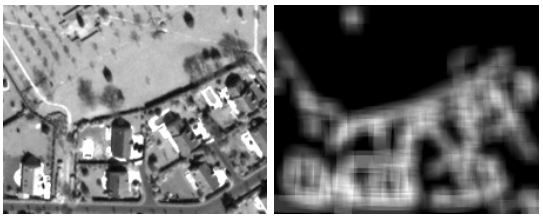


Figure 14.11: Result of applying the `otb::EdgeDensityImageFilter` to an image. From left to right : original image, edge density.

```
cannyFilter->SetUpperThreshold(upperThreshold);
cannyFilter->SetLowerThreshold(lowerThreshold);
cannyFilter->SetVariance(variance);
cannyFilter->SetMaximumError(maximumError);
```

After that, we can pass the edge detector to the filter which will be used it internally.

```
filter->SetDetector(cannyFilter);
filter->SetNeighborhoodRadius(radius);
```

Finally, we set the file names for the input and the output images and we plug the pipeline. The `Update()` method of the writer will trigger the processing.

```
reader->SetFileName(infname);
writer->SetFileName(outfname);

filter->SetInput(reader->GetOutput());
writer->SetInput(filter->GetOutput());
writer->Update();
```

Figure 14.11 shows the result of applying the edge density filter to an image.

14.5.2 SIFT Density

14.6 Geometric Moments

14.6.1 Complex Moments

The complex geometric moments are defined as:

$$c_{pq} = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} (x+iy)^p (x-iy)^q f(x,y)dxdy, \tag{14.2}$$

where x and y are the coordinates of the image $f(x,y)$, i is the imaginary unit and $p+q$ is the order of c_{pq}. The geometric moments are particularly useful in the case of scale changes.

Complex Moments for Images

The source code for this example can be found in the file
`Examples/FeatureExtraction/ComplexMomentsImageFunctionExample.cxx`.

This example illustrates the use of the `otb::ComplexMomentsImageFunction`.

The first step required to use this filter is to include its header file.

```
#include "otbComplexMomentsImageFunction.h"
```

The `otb::ComplexMomentImageFunction` is templated over the input image type and the output complex type value, so we start by defining:

```
typedef otb::ComplexMomentsImageFunction<InputImageType> CMType;
typedef CMType::OutputType OutputType;

CMType::Pointer cmFunction = CMType::New();
```

Next, we plug the input image into the complex moment fucntion and we set its parameters.

```
reader->Update();
cmFunction->SetInputImage(reader->GetOutput());
cmFunction->SetQmax(Q);
cmFunction->SetPmax(P);
```

We can chose the pixel of the image which will used as center for the moment computation

```
InputImageType::IndexType center;
center[0] = 50;
center[1] = 50;
```

We can also choose the size of the neighborhood around the center pixel for the moment computation.

In order to get the value of the moment, we call the `EvaluateAtIndex` method.

```
OutputType Result = cmFunction->EvaluateAtIndex(center);

std::cout << "The moment of order (" << P << "," << Q <<
") is equal to " << Result.at(P).at(Q) << std::endl;
```

Complex Moments for Paths

The source code for this example can be found in the file
`Examples/FeatureExtraction/ComplexMomentPathExample.cxx`.

The complex moments can be computed on images, but sometimes we are interested in computing them on shapes extracted from images by segmentation algorithms. These shapes can be represented by itk::Paths. This example illustrates the use of the otb::ComplexMomentPathFunction for the computation of complex geometric moments on ITK paths.

The first step required to use this filter is to include its header file.

```
#include "otbComplexMomentPathFunction.h"
```

The otb::ComplexMomentPathFunction is templated over the input path type and the output complex type value, so we start by defining:

```
const unsigned int Dimension = 2;

typedef itk::PolyLineParametricPath<Dimension> PathType;

typedef std::complex<double>                                    ComplexType;
typedef otb::ComplexMomentPathFunction<PathType, ComplexType> CMType;

CMType::Pointer cmFunction = CMType::New();
```

Next, we set the parameters of the plug the input path into the complex moment function and we set its parameters.

```
cmFunction->SetInputPath(path);
cmFunction->SetQ(Q);
cmFunction->SetP(P);
```

Since the paths are defined in physical coordinates, we do not need to set the center for the moment computation as we did with the otb::ComplexMomentImageFunction. The same applies for the size of the neighborhood around the center pixel for the moment computation. The moment computation is triggered by calling the Evaluate method.

```
ComplexType Result = cmFunction->Evaluate();

std::cout << "The moment of order (" << P << "," << Q <<
") is equal to " << Result << std::endl;
```

14.6.2 Hu Moments

Using the algebraic moment theory, H. Ming-Kuel obtained a family of 7 invariants with respect to planar transformations called Hu invariants, [60]. Those invariants can be seen as nonlinear combinations of the complex moments. Hu invariants have been very much used in object recognition during the last 30 years, since they are invariant to rotation, scaling and translation. [46] gives their expressions :

$$\begin{array}{cccc} \phi_1 = c_{11}; & \phi_2 = c_{20}c_{02}; & \phi_3 = c_{30}c_{03}; & \phi_4 = c_{21}c_{12}; \\ \phi_5 = Re(c_{30}c_{12}^3); & \phi_6 = Re(c_{21}c_{12}^2); & \phi_7 = Im(c_{30}c_{12}^3). & \end{array} \tag{14.3}$$

[42] have used these invariants for the recognition of aircraft silhouettes. Flusser and Suk have used them for image registration, [72].

Hu Moments for Images

The source code for this example can be found in the file `Examples/FeatureExtraction/HuMomentsImageFunctionExample.cxx`.

This example illustrates the use of the `otb::HuMomentsImageFunction`.

The first step required to use this filter is to include its header file.

```
#include "otbHuMomentsImageFunction.h"
```

The `otb::HuImageFunction` is templated over the input image type and the output (real) type value, so we start by defining:

```
typedef otb::HuMomentsImageFunction<InputImageType>  HuType;
typedef HuType::OutputType                           MomentType;

HuType::Pointer hmFunction = HuType::New();
```

We can choose the region and the pixel of the image which will used as coordinate origin for the moment computation

```
InputImageType::RegionType region;
InputImageType::SizeType   size;
InputImageType::IndexType  start;

start[0] = 0;
start[1] = 0;
size[0] = 50;
size[1] = 50;

reader->Update();
InputImageType::Pointer image = reader->GetOutput();

region.SetIndex(start);
region.SetSize(size);

image->SetRegions(region);
image->Update();

InputImageType::IndexType center;
center[0] = start[0] + size[0] / 2;
center[1] = start[1] + size[1] / 2;
```

Next, we plug the input image into the complex moment function and we set its parameters.

```
hmFunction->SetInputImage(image);
hmFunction->SetNeighborhoodRadius(radius);
```

In order to get the value of the moment, we call the `EvaluateAtIndex` method.

```
MomentType Result = hmFunction->EvaluateAtIndex(center);

for (unsigned int j=0; j<7; ++j)
  {
  std::cout << "The moment of order " << j+1 <<
    " is equal to " << Result[j] << std::endl;
  }
```

The following classes provide similar functionality:

- `otb::HuPathFunction`

14.6.3 Flusser Moments

The Hu invariants have been modified and improved by several authors. Flusser used these moments in order to produce a new family of descriptors of order higher than 3, [46]. These descriptors are invariant to scale and rotation. They have the following expressions:

$$\begin{array}{ccc} \psi_1 = c_{11} = \phi_1; & \psi_2 = c_{21}c_{12} = \phi_4; & \psi_3 = Re(c_{20}c_{12}^2) = \phi_6; \\ \psi_4 = Im(c_{20}c_{12}^2); & \psi_5 = Re(c_{30}c_{12}^3) = \phi_5; & \psi_6 = Im(c_{30}c_{12}^3) = \phi_7. \\ \psi_7 = c_{22}; & \psi_8 = Re(c_{31}c_{12}^2); & \psi_9 = Im(c_{31}c_{12}\ 2); \\ \psi_{10} = Re(c_{40}c_{12}^4); & \psi_{11} = Im(c_{40}c_{12}^2). & \end{array} \tag{14.4}$$

Examples

Flusser Moments for Images

The source code for this example can be found in the file `Examples/FeatureExtraction/FlusserMomentsImageFunctionExample.cxx`.

This example illustrates the use of the `otb::FlusserMomentsImageFunction`.

The first step required to use this filter is to include its header file.

```
#include "otbFlusserMomentsImageFunction.h"
```

The `otb::FlusserMomentsImageFunction` is templated over the input image type and the output (real) type value, so we start by defining:

```
typedef otb::FlusserMomentsImageFunction<InputImageType>  FlusserType;
typedef FlusserType::OutputType                           MomentType;

FlusserType::Pointer fmFunction = FlusserType::New();
```

We can choose the region and the pixel of the image which will used as coordinate origin for the moment computation

```
InputImageType::RegionType region;
InputImageType::SizeType   size;
InputImageType::IndexType  start;

start[0] = 0;
start[1] = 0;
size[0] = 50;
size[1] = 50;

reader->Update();
InputImageType::Pointer image = reader->GetOutput();

region.SetIndex(start);
region.SetSize(size);

image->SetRegions(region);
image->Update();

InputImageType::IndexType center;
center[0] = start[0] + size[0] / 2;
center[1] = start[1] + size[1] / 2;
```

Next, we plug the input image into the complex moment function and we set its parameters.

```
fmFunction->SetInputImage(image);
fmFunction->SetNeighborhoodRadius(radius);
```

In order to get the value of the moment, we call the `EvaluateAtIndex` method.

```
MomentType Result = fmFunction->EvaluateAtIndex(center);

for (unsigned int j=0; j<11; ++j)
  {
  std::cout << "The moment of order " << j+1 <<
    " is equal to " << Result[j] << std::endl;
  }
```

The following classes provide similar functionality:

- `otb::FlusserPathFunction`

14.7 Road extraction

Road extraction is a critical feature for an efficient use of high resolution satellite images. There are many applications of road extraction: update of GIS database, reference for image registration, help for identification algorithms and rapid mapping for example. Road network can be used to register

an optical image with a map or an optical image with a radar image for example. Road network extraction can help for other algorithms: isolated building detection, bridge detection. In these cases, a rough extraction can be sufficient. In the context of response to crisis, a fast mapping is necessary: within 6 hours, infrastructures for the designated area are required. Within this timeframe, a manual extraction is inconceivable and an automatic help is necessary.

14.7.1 Road extraction filter

The source code for this example can be found in the file
`Examples/FeatureExtraction/ExtractRoadExample.cxx`.

The easiest way to use the road extraction filter provided by OTB is to use the composite filter. If a modification in the pipeline is required to adapt to a particular situation, the step by step example, described in the next section can be adapted.

This example demonstrates the use of the `otb::RoadExtractionFilter`. This filter is a composite filter achieving road extraction according to the algorithm adapted by E. Christophe and J. Inglada [24] from an original method proposed in [83].

The first step toward the use of this filter is the inclusion of the proper header files.

```
#include "otbPolyLineParametricPathWithValue.h"
#include "otbRoadExtractionFilter.h"
#include "otbDrawPathListFilter.h"
```

Then we must decide what pixel type to use for the image. We choose to do all the computation in floating point precision and rescale the results between 0 and 255 in order to export PNG images.

```
  typedef double         InputPixelType;
  typedef unsigned char  OutputPixelType;
```

The images are defined using the pixel type and the dimension. Please note that the `otb::RoadExtractionFilter` needs an `otb::VectorImage` as input to handle multispectral images.

```
  typedef otb::VectorImage<InputPixelType, Dimension> InputVectorImageType;
  typedef otb::Image<InputPixelType, Dimension>       InputImageType;
  typedef otb::Image<OutputPixelType, Dimension>      OutputImageType;
```

We define the type of the polyline that the filter produces. We use the `otb::PolyLineParametricPathWithValue`, which allows the filter to produce a likehood value along with each polyline. The filter is able to produce `itk::PolyLineParametricPath` as well.

```
  typedef otb::PolyLineParametricPathWithValue<InputPixelType,
      Dimension> PathType;
```

Now we can define the otb::RoadExtractionFilter that takes a multi-spectral image as input and produces a list of polylines.

```
typedef otb::RoadExtractionFilter<InputVectorImageType,
    PathType> RoadExtractionFilterType;
```

We also define an otb::DrawPathListFilter to draw the output polylines on an image, taking their likehood values into account.

```
typedef otb::DrawPathListFilter<InputImageType, PathType,
    InputImageType> DrawPathFilterType;
```

The intensity rescaling of the results will be carried out by the itk::RescaleIntensityImageFilter which is templated by the input and output image types.

```
typedef itk::RescaleIntensityImageFilter<InputImageType,
    OutputImageType> RescalerType;
```

An otb::ImageFileReader class is also instantiated in order to read image data from a file. Then, an otb::ImageFileWriter is instantiated in order to write the output image to a file.

```
typedef otb::ImageFileReader<InputVectorImageType> ReaderType;
typedef otb::ImageFileWriter<OutputImageType>      WriterType;
```

The different filters composing our pipeline are created by invoking their New() methods, assigning the results to smart pointers.

```
ReaderType::Pointer                reader = ReaderType::New();
RoadExtractionFilterType::Pointer roadExtractionFilter
  = RoadExtractionFilterType::New();
DrawPathFilterType::Pointer drawingFilter = DrawPathFilterType::New();
RescalerType::Pointer       rescaleFilter = RescalerType::New();
WriterType::Pointer         writer = WriterType::New();
```

The otb::RoadExtractionFilter needs to have a reference pixel corresponding to the spectral content likely to represent a road. This is done by passing a pixel to the filter. Here we suppose that the input image has four spectral bands.

```
InputVectorImageType::PixelType ReferencePixel;
ReferencePixel.SetSize(4);
ReferencePixel.SetElement(0, ::atof(argv[3]));
ReferencePixel.SetElement(1, ::atof(argv[4]));
ReferencePixel.SetElement(2, ::atof(argv[5]));
ReferencePixel.SetElement(3, ::atof(argv[6]));
roadExtractionFilter->SetReferencePixel(ReferencePixel);
```

We must also set the alpha parameter of the filter which allows us to tune the width of the roads we want to extract. Typical value is 1.0 and should be working in most situations.

```
roadExtractionFilter->SetAlpha(atof(argv[7]));
```

All other parameter should not influence the results too much in most situation and can be kept at the default value.

The amplitude threshold parameter tunes the sensitivity of the vectorization step. A typical value is $5 \cdot 10^{-5}$.

```
roadExtractionFilter->SetAmplitudeThreshold(atof(argv[8]));
```

The tolerance threshold tunes the sensitivity of the path simplification step. Typical value is 1.0.

```
roadExtractionFilter->SetTolerance(atof(argv[9]));
```

Roads are not likely to have sharp turns. Therefore we set the max angle parameter, as well as the link angular threshold. The value is typicaly $\frac{\pi}{8}$.

```
roadExtractionFilter->SetMaxAngle(atof(argv[10]));
roadExtractionFilter->SetAngularThreshold(atof(argv[10]));
```

The `otb::RoadExtractionFilter` performs two odd path removing operations at different stage of its execution. The first mean distance threshold and the second mean distance threshold set their criterion for removal. Path are removed if their mean distance between nodes is to small, since such path coming from previous filters are likely to be tortuous. The first removal operation as a typical mean distance threshold parameter of 1.0, and the second of 10.0.

```
roadExtractionFilter->SetFirstMeanDistanceThreshold(atof(argv[11]));
roadExtractionFilter->SetSecondMeanDistanceThreshold(atof(argv[12]));
```

The `otb::RoadExtractionFilter` is able to link path whose ends are near according to an euclidean distance criterion. The threshold for this distance to link a path is the distance threshold parameter. A typical value is 25.

```
roadExtractionFilter->SetDistanceThreshold(atof(argv[13]));
```

We will now create a black background image to draw the resulting polyline on. To achieve this we need to know the size of our input image. Therefore we trigger the `GenerateOutputInformation()` of the reader.

```
reader->GenerateOutputInformation();
InputImageType::Pointer blackBackground = InputImageType::New();
blackBackground->SetRegions(reader->GetOutput()->GetLargestPossibleRegion());
blackBackground->Allocate();
blackBackground->FillBuffer(0);
```

We tell the `otb::DrawPathListFilter` to try to use the likehood value embedded within the polyline as a value for drawing this polyline if possible.

Figure 14.12: Result of applying the `otb::RoadExtractionFilter` to a fusionned Quickbird image. From left to right : original image, extracted road with their likehood values (color are inverted for display).

```
drawingFilter->UseInternalPathValueOn();
```

The `itk::RescaleIntensityImageFilter` needs to know which is the minimum and maximum values of the output generated image. Those can be chosen in a generic way by using the `NumericTraits` functions, since they are templated over the pixel type.

```
rescaleFilter->SetOutputMinimum(itk::NumericTraits<OutputPixelType>::min());
rescaleFilter->SetOutputMaximum(itk::NumericTraits<OutputPixelType>::max());
```

Now it is time for some pipeline wiring.

```
roadExtractionFilter->SetInput(reader->GetOutput());
drawingFilter->SetInput(blackBackground);
drawingFilter->SetInputPath(roadExtractionFilter->GetOutput());
rescaleFilter->SetInput(drawingFilter->GetOutput());
```

The update of the pipeline is triggered by the `Update()` method of the rescale intensity filter.

```
rescaleFilter->Update();
```

Figure 14.12 shows the result of applying the road extraction filter to a fusionned Quickbird image.

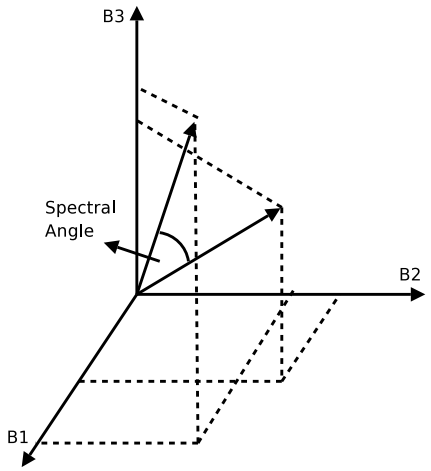


Figure 14.13: Illustration of the spectral angle for one pixel of a three-band image. One of the vector is the reference pixel and the other is the current pixel.

14.7.2 Step by step road extraction

The source code for this example can be found in the file
`Examples/FeatureExtraction/ExtractRoadByStepsExample.cxx`.

This example illustrates the details of the `otb::RoadExtractionFilter`. This filter, described in the previous section, is a composite filter that includes all the steps below. Individual filters can be replaced to design a road detector targeted at SAR images for example.

The spectral angle is used to compute a grayscale image from the multispectral original image using `otb::SpectralAngleDistanceImageFilter`. The spectral angle is illustrated on Figure 14.13. Pixels corresponding to roads are in darker color.

```
typedef otb::SpectralAngleDistanceImageFilter<MultiSpectralImageType,
    InternalImageType> SAFilterType;
SAFilterType::Pointer saFilter = SAFilterType::New();
saFilter->SetReferencePixel(pixelRef);
saFilter->SetInput(multispectralReader->GetOutput());
```

A square root is applied to the spectral angle image in order to enhance contrast between darker pixels (which are pixels of interest) with `itk::SqrtImageFilter`.

```
typedef itk::SqrtImageFilter<InternalImageType,
    InternalImageType> SqrtFilterType;
SqrtFilterType::Pointer sqrtFilter = SqrtFilterType::New();
sqrtFilter->SetInput(saFilter->GetOutput());
```

Use the Gaussian gradient filter compute the gradient in x and y direction respectively (itk::GradientRecursiveGaussianImageFilter).

```
double sigma = alpha * (1.2 / resolution + 1);
typedef itk::GradientRecursiveGaussianImageFilter<InternalImageType,
    VectorImageType>
GradientFilterType;
GradientFilterType::Pointer gradientFilter = GradientFilterType::New();
gradientFilter->SetSigma(sigma);
gradientFilter->SetInput(sqrtFilter->GetOutput());
```

Compute the scalar product of the neighboring pixels and keep the minimum value and the direction with otb::NeighborhoodScalarProductFilter. This is the line detector described in [83].

```
typedef otb::NeighborhoodScalarProductFilter<VectorImageType,
    InternalImageType,
    InternalImageType>
NeighborhoodScalarProductType;
NeighborhoodScalarProductType::Pointer scalarFilter
  = NeighborhoodScalarProductType::New();
scalarFilter->SetInput(gradientFilter->GetOutput());
```

The resulting image is passed to the otb::RemoveIsolatedByDirectionFilter filter to remove pixels with no neighbor having the same direction.

```
typedef otb::RemoveIsolatedByDirectionFilter<InternalImageType,
    InternalImageType,
    InternalImageType>
RemoveIsolatedByDirectionType;
RemoveIsolatedByDirectionType::Pointer removeIsolatedByDirectionFilter
  = RemoveIsolatedByDirectionType::New();
removeIsolatedByDirectionFilter->SetInput(scalarFilter->GetOutput());
removeIsolatedByDirectionFilter
->SetInputDirection(scalarFilter->GetOutputDirection());
```

We remove pixels having a direction corresponding to bright lines as we know that after the spectral angle, roads are in darker color with the otb::RemoveWrongDirectionFilter filter.

```
typedef otb::RemoveWrongDirectionFilter<InternalImageType,
    InternalImageType,
    InternalImageType>
RemoveWrongDirectionType;
RemoveWrongDirectionType::Pointer removeWrongDirectionFilter
  = RemoveWrongDirectionType::New();
removeWrongDirectionFilter->SetInput(
  removeIsolatedByDirectionFilter->GetOutput());
removeWrongDirectionFilter->SetInputDirection(
  scalarFilter->GetOutputDirection());
```

We remove pixels which are not maximum on the direction perpendicular to the road direction with the otb::NonMaxRemovalByDirectionFilter.

```
typedef otb::NonMaxRemovalByDirectionFilter<InternalImageType,
    InternalImageType,
    InternalImageType>
NonMaxRemovalByDirectionType;
NonMaxRemovalByDirectionType::Pointer nonMaxRemovalByDirectionFilter
  = NonMaxRemovalByDirectionType::New();
nonMaxRemovalByDirectionFilter->SetInput(
  removeWrongDirectionFilter->GetOutput());
nonMaxRemovalByDirectionFilter
->SetInputDirection(scalarFilter->GetOutputDirection());
```

Extracted road are vectorized into polylines with `otb::VectorizationPathListFilter`.

```
typedef otb::VectorizationPathListFilter<InternalImageType,
    InternalImageType,
    PathType> VectorizationFilterType;
VectorizationFilterType::Pointer vectorizationFilter
  = VectorizationFilterType::New();
vectorizationFilter->SetInput(nonMaxRemovalByDirectionFilter->GetOutput());
vectorizationFilter->SetInputDirection(scalarFilter->GetOutputDirection());
vectorizationFilter->SetAmplitudeThreshold(atof(argv[8]));
```

However, this vectorization is too simple and need to be refined to be usable. First, we remove all aligned points to make one segment with `otb::SimplifyPathListFilter`. Then we break the polylines which have sharp angles as they are probably not road with `otb::BreakAngularPathListFilter`. Finally we remove path which are too short with `otb::RemoveTortuousPathListFilter`.

```
typedef otb::SimplifyPathListFilter<PathType> SimplifyPathType;
SimplifyPathType::Pointer simplifyPathListFilter = SimplifyPathType::New();
simplifyPathListFilter->GetFunctor().SetTolerance(1.0);
simplifyPathListFilter->SetInput(vectorizationFilter->GetOutput());

typedef otb::BreakAngularPathListFilter<PathType> BreakAngularPathType;
BreakAngularPathType::Pointer breakAngularPathListFilter
  = BreakAngularPathType::New();
breakAngularPathListFilter->SetMaxAngle(otb::CONST_PI / 8.);
breakAngularPathListFilter->SetInput(simplifyPathListFilter->GetOutput());

typedef otb::RemoveTortuousPathListFilter<PathType> RemoveTortuousPathType;
RemoveTortuousPathType::Pointer removeTortuousPathListFilter
  = RemoveTortuousPathType::New();
removeTortuousPathListFilter->GetFunctor().SetThreshold(1.0);
removeTortuousPathListFilter->SetInput(breakAngularPathListFilter->GetOutput());
```

Polylines within a certain range are linked (`otb::LinkPathListFilter`) to try to fill gaps due to occultations by vehicules, trees, etc. before simplifying polylines (`otb::SimplifyPathListFilter`) and removing the shortest ones with `otb::RemoveTortuousPathListFilter`.

```
typedef otb::LinkPathListFilter<PathType> LinkPathType;
```

```
LinkPathType::Pointer linkPathListFilter = LinkPathType::New();
linkPathListFilter->SetDistanceThreshold(25.0 / resolution);
linkPathListFilter->SetAngularThreshold(otb::CONST_PI / 8);
linkPathListFilter->SetInput(removeTortuousPathListFilter->GetOutput());

SimplifyPathType::Pointer simplifyPathListFilter2 = SimplifyPathType::New();
simplifyPathListFilter2->GetFunctor().SetTolerance(1.0);
simplifyPathListFilter2->SetInput(linkPathListFilter->GetOutput());

RemoveTortuousPathType::Pointer removeTortuousPathListFilter2
  = RemoveTortuousPathType::New();
removeTortuousPathListFilter2->GetFunctor().SetThreshold(10.0);
removeTortuousPathListFilter2->SetInput(simplifyPathListFilter2->GetOutput());
```

A value can be associated with each polyline according to pixel values under the polyline with `otb::LikelihoodPathListFilter`. A higher value will mean a higher Likelihood to be a road.

```
typedef otb::LikelihoodPathListFilter<PathType,
    InternalImageType>
PathListToPathListWithValueType;
PathListToPathListWithValueType::Pointer pathListConverter
  = PathListToPathListWithValueType::New();
pathListConverter->SetInput(removeTortuousPathListFilter2->GetOutput());
pathListConverter->SetInputImage(nonMaxRemovalByDirectionFilter->GetOutput());
```

A black background image is built to draw the path on.

```
InternalImageType::Pointer output = InternalImageType::New();
output->SetRegions(multispectralReader->GetOutput()
                   ->GetLargestPossibleRegion());
output->Allocate();
output->FillBuffer(0.0);
output->SetOrigin(multispectralReader->GetOutput()->GetOrigin());
output->SetSpacing(multispectralReader->GetOutput()->GetSpacing());
```

Polylines are drawn on a black background image with `otb::DrawPathListFilter`. The `SetUseIternalValues()` tell the drawing filter to draw the path with its Likelihood value.

```
typedef otb::DrawPathListFilter<InternalImageType, PathType,
    InternalImageType> DrawPathType;
DrawPathType::Pointer drawPathListFilter = DrawPathType::New();
drawPathListFilter->SetInput(output);
drawPathListFilter->SetInputPath(pathListConverter->GetOutput());
drawPathListFilter->SetUseInternalPathValue(true);
```

The output from the drawing filter contains very small values (Likelihood values). Therefore the image has to be rescaled to be viewed. The whole pipeline is executed by invoking the `Update()` method on this last filter.

```
typedef itk::RescaleIntensityImageFilter<InternalImageType,
    InternalImageType> RescalerType;
RescalerType::Pointer rescaler = RescalerType::New();
```

```
rescaler->SetOutputMaximum(255);
rescaler->SetOutputMinimum(0);
rescaler->SetInput(drawPathListFilter->GetOutput());
rescaler->Update();
```

Figures 14.14 and 14.15 show the result of applying the road extraction by steps to a fusionned Quickbird image. The result image is a RGB composition showing the extracted path in red. Full processing took about 3 seconds for each image.

Figure 14.14: Result of applying the road extraction by steps pipeline to a fusionned Quickbird image. From left to right : original image, extracted road with their Likelihood values.

14.8 Cloud Detection

The source code for this example can be found in the file
`Examples/FeatureExtraction/CloudDetectionExample.cxx`.

The cloud detection functor is a processing chain composed by the computation of a spectral angle (with SpectralAngleFunctor). The result is multiplied by a gaussian factor (with CloudEstimator-Functor) and finally thresholded to obtain a binary image (with CloudDetectionFilter). However, modifications can be added in the pipeline to adapt to a particular situation.

This example demonstrates the use of the `otb::CloudDetectionFilter`. This filter uses the spectral angle principle to measure the radiometric gap between a reference pixel and the other pixels of the image.

The first step toward the use of this filter is the inclusion of the proper header files.

Figure 14.15: Result of applying the road extraction by steps pipeline to a fusionned Quickbird image. From left to right : original image, extracted road with their Likelihood values.

```
#include "otbCloudDetectionFunctor.h"
#include "otbCloudDetectionFilter.h"
```

Then we must decide what pixel type to use for the images. We choose to do all the computations in double precision.

```
typedef double InputPixelType;
typedef double OutputPixelType;
```

The images are defined using the pixel type and the dimension. Please note that the `otb::CloudDetectionFilter` needs an `otb::VectorImage` as input to handle multispectral images.

```
typedef otb::VectorImage<InputPixelType, Dimension> VectorImageType;
typedef VectorImageType::PixelType                  VectorPixelType;
typedef otb::Image<OutputPixelType, Dimension>      OutputImageType;
```

We define the functor type that the filter will use. We use the `otb::CloudDetectionFunctor`.

```
typedef otb::Functor::CloudDetectionFunctor<VectorPixelType,
    OutputPixelType>   FunctorType;
```

Now we can define the `otb::CloudDetectionFilter` that takes a multi-spectral image as input and produces a binary image.

```
typedef otb::CloudDetectionFilter<VectorImageType, OutputImageType,
    FunctorType> CloudDetectionFilterType;
```

An otb::ImageFileReader class is also instantiated in order to read image data from a file. Then, an otb::ImageFileWriter is instantiated in order to write the output image to a file.

```
typedef otb::ImageFileReader<VectorImageType> ReaderType;
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

The different filters composing our pipeline are created by invoking their New() methods, assigning the results to smart pointers.

```
ReaderType::Pointer                reader = ReaderType::New();
CloudDetectionFilterType::Pointer cloudDetection =
  CloudDetectionFilterType::New();
WriterType::Pointer writer = WriterType::New();
```

The otb::CloudDetectionFilter needs to have a reference pixel corresponding to the spectral content likely to represent a cloud. This is done by passing a pixel to the filter. Here we suppose that the input image has four spectral bands.

```
VectorPixelType referencePixel;
referencePixel.SetSize(4);
referencePixel.Fill(0.);
referencePixel[0] = (atof(argv[5]));
referencePixel[1] = (atof(argv[6]));
referencePixel[2] = (atof(argv[7]));
referencePixel[3] = (atof(argv[8]));
cloudDetection->SetReferencePixel(referencePixel);
```

We must also set the variance parameter of the filter and the parameter of the gaussian functor. The bigger the value, the more tolerant the detector will be.

```
cloudDetection->SetVariance(atof(argv[9]));
```

The minimum and maximum thresholds are set to binarise the final result. These values have to be between 0 and 1.

```
cloudDetection->SetMinThreshold(atof(argv[10]));
cloudDetection->SetMaxThreshold(atof(argv[11]));
```

```
writer->SetFileName(argv[2]);
writer->SetInput(cloudDetection->GetOutput());
writer->Update();
```

Figure 14.16 shows the result of applying the cloud detection filter to a cloudy image.

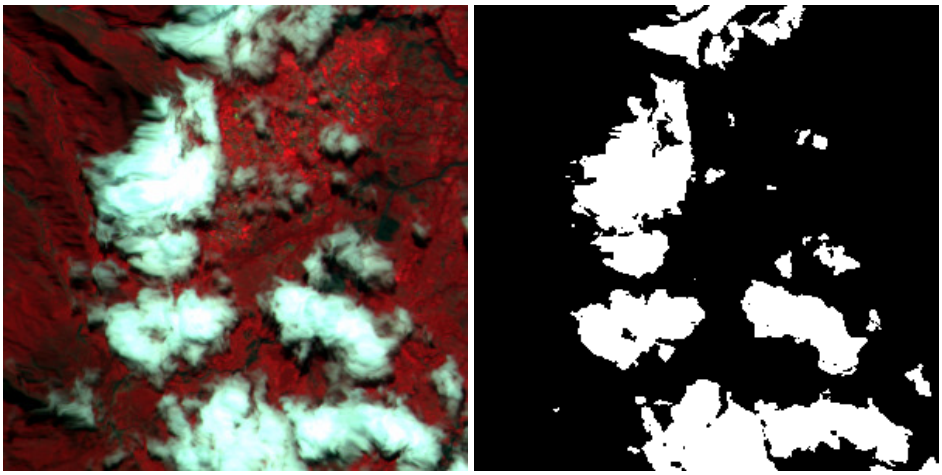


Figure 14.16: From left to right : original image, cloud mask resulting from processing.

CHAPTER

FIFTEEN

MULTI-SCALE ANALYSIS

15.1 Introduction

In this chapter, the tools for multi-scale and multi-resoltuion processing (analysis, synthesis and fusion) will be presented. Most of the algorithms are based on pyramidal approaches. These approaches were first used for image compression and they are based on the fact that, once an image has been low-pass filtered it does not have details beyond the cut-off frequency of the low-pass filter any more. Therefore, the image can be subsampled – decimated – without any loss of information.

A pyramidal decomposition is thus performed applying the following 3 steps in an iterative way:

1. Low pas filter the image I_n in order to produce $F(I_n)$;
2. Compute the difference $D_n = I_n - F(I_n)$ which corresponds to the details at level n;
3. Subsample $F(I_n)$ in order to obtain I_{n+1}.

The result is a series of decrasing resolution images I_k and a series of decreasing resolution details D_k.

15.2 Morphological Pyramid

If the smoothing filter used in the pyramidal analysis is a morphological filter, one cannot safely subsample the filtered image without loss of information. However, by keeping the details possibly lost in the down-sampling operation, such a decomposition can be used.

The Morphological Pyramid is an approach to such a decomposition. Its computation process is an iterative analysis involving smoothing by the morphological filter, computing the details lost in the smoothing, down-sampling the current image, and computing the details lost in the down-sampling.

The source code for this example can be found in the file
`Examples/MultiScale/MorphologicalPyramidAnalysisFilterExample.cxx`.

This example illustrates the use of the `otb::MorphologicalPyramidAnalyseFilter`.

The first step required to use this filter is to include its header file.

```
#include "otbMorphologicalPyramidAnalysisFilter.h"
```

The mathematical morphology filters to be used have also to be included here.

```
#include "otbOpeningClosingMorphologicalFilter.h"
#include "itkBinaryBallStructuringElement.h"
```

As usual, we start by defining the types needed for the pixels, the images, the image reader and the image writer.

```
  const unsigned int Dimension = 2;
  typedef unsigned char InputPixelType;
  typedef unsigned char OutputPixelType;

  typedef otb::Image<InputPixelType, Dimension>  InputImageType;
  typedef otb::Image<OutputPixelType, Dimension> OutputImageType;

  typedef otb::ImageFileReader<InputImageType>  ReaderType;
  typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

Now, we define the types needed for the morphological filters which will be used to build the morphological pyramid. The first thing to do is define the structuring element, which in our case, will be a `itk::BinaryBallStructuringElement` which is templated over the pixel type and the dimension of the image.

```
  typedef itk::BinaryBallStructuringElement<InputPixelType,
      Dimension> StructuringElementType;
```

We can now define the type of the filter to be used by the morphological pyramid. In this case, we choose to use an `otb::OpeningClosingMorphologicalFilter` which is just the concatenation of an opening and a closing. This filter is templated over the input and output image types and the structuring element type that we just define above.

```
  typedef otb::OpeningClosingMorphologicalFilter<InputImageType,
      InputImageType,
      StructuringElementType>
  OpeningClosingFilterType;
```

We can finally define the type of the morpholoical pyramid filter. The filter is templated over the input and output image types and the *lowpas* morphological filter to be used.

```
  typedef otb::MorphologicalPyramidAnalysisFilter<InputImageType,
      OutputImageType,
```

```
    OpeningClosingFilterType>
PyramidFilterType;
```

Since the otb::MorphologicalPyramidAnalyseFilter generates a list of images as output, it is useful to have an iterator to access the images. This is done as follows :

```
typedef PyramidFilterType::OutputImageListType::Iterator
ImageListIterator;
```

We can now instantiate the reader in order to access the input image which has to be analysed.

```
ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(inputFilename);
```

We instantiate the morphological pyramid analysis filter and set its parameters which are:

- the number of iterations or levels of the pyramid;
- the subsample scale or decimation factor between two successive pyramid levels.

After that, we plug the pipeline and run it by calling the Update() method.

```
PyramidFilterType::Pointer pyramid = PyramidFilterType::New();
pyramid->SetNumberOfLevels(numberOfLevels);
pyramid->SetDecimationRatio(decimationRatio);
pyramid->SetInput(reader->GetOutput());
pyramid->Update();
```

The morphological pyramid has 5 types of output:

- the analysed image at each level of the pyramid through the GetOutput() method;
- the brighter details extracted from the filtering operation through the GetSupFilter() method;
- the darker details extracted from the filtering operation through the GetInfFilter() method;
- the brighter details extracted from the resampling operation through the GetSupDeci() method;
- the darker details extracted from the resampling operation through the GetInfDeci() method; to decimation

Each one of these methods provides a list of images (one for each level of analysis), so we can iterate through the image lists by using iterators.

```
ImageListIterator itAnalyse = pyramid->GetOutput()->Begin();
ImageListIterator itSupFilter = pyramid->GetSupFilter()->Begin();
ImageListIterator itInfFilter = pyramid->GetInfFilter()->Begin();
ImageListIterator itInfDeci = pyramid->GetSupDeci()->Begin();
ImageListIterator itSupDeci =  pyramid->GetInfDeci()->Begin();
```

We can now instantiate a writer and use it to write all the images to files.

```
  WriterType::Pointer writer =  WriterType::New();

  int i = 1;

  // Writing the results images
  std::cout << (itAnalyse != (pyramid->GetOutput()->End())) << std::endl;
  while (itAnalyse != pyramid->GetOutput()->End())
    {
    writer->SetInput(itAnalyse.Get());
    writer->SetFileName(argv[0 * 4 + i + 1]);
    writer->Update();

    writer->SetInput(itSupFilter.Get());
    writer->SetFileName(argv[1 * 4 + i + 1]);
    writer->Update();

    writer->SetInput(itInfFilter.Get());
    writer->SetFileName(argv[2 * 4 + i + 1]);
    writer->Update();

    writer->SetInput(itInfDeci.Get());
    writer->SetFileName(argv[3 * 4 + i + 1]);
    writer->Update();

    writer->SetInput(itSupDeci.Get());
    writer->SetFileName(argv[4 * 4 + i + 1]);
    writer->Update();

    ++itAnalyse;
    ++itSupFilter;
    ++itInfFilter;
    ++itInfDeci;
    ++itSupDeci;
    ++i;
    }
```

Figure 15.1 shows the test image to be processed by the morphological pyramid.

Figure 15.2 shows the 4 levels of analysis of the image.

Figure 15.3 shows the 4 levels of bright details.

Figure 15.4 shows the 4 levels of dark details.

Figure 15.5 shows the 4 levels of bright decimation details.

Figure 15.6 shows the 4 levels of dark decimation details.

The source code for this example can be found in the file
`Examples/MultiScale/MorphologicalPyramidSynthesisFilterExample.cxx`.

This example illustrates the use of the `otb::MorphologicalPyramidSynthesisFilter`.

Figure 15.1: Test image for the morphological pyramid.

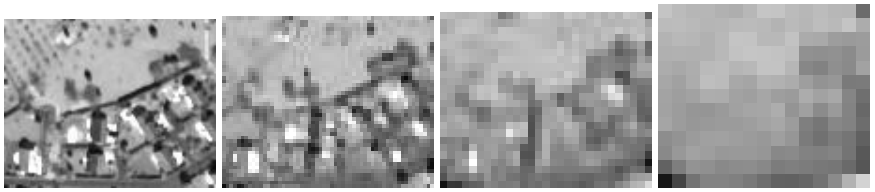


Figure 15.2: Result of the analysis for 4 levels of the pyramid.

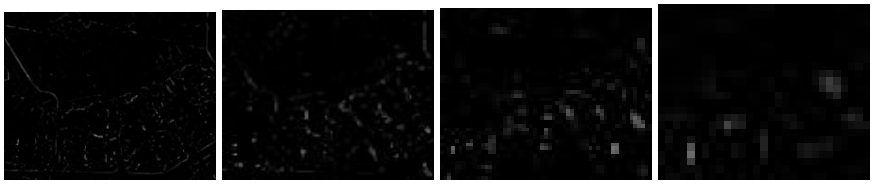


Figure 15.3: Bright details for 4 levels of the pyramid.

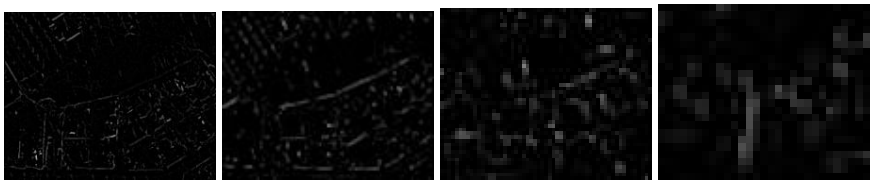


Figure 15.4: Dark details for 4 levels of the pyramid.

Figure 15.5: Bright decimation details for 4 levels of the pyramid.

Figure 15.6: Dark decimation details for 4 levels of the pyramid.

The first step required to use this filter is to include its header file.

```
#include "otbMorphologicalPyramidSynthesisFilter.h"
```

The mathematical morphology filters to be used have also to be included here, as well as the `otb::MorphologicalPyramidAnalyseFilter` in order to perform the analysis step.

```
#include "otbMorphologicalPyramidAnalysisFilter.h"
#include "otbOpeningClosingMorphologicalFilter.h"
#include "itkBinaryBallStructuringElement.h"
```

As usual, we start by defining the types needed for the pixels, the images, the image reader and the image writer.

```
  const unsigned int Dimension = 2;
  typedef unsigned char InputPixelType;
  typedef unsigned char OutputPixelType;

  typedef otb::Image<InputPixelType, Dimension>  InputImageType;
  typedef otb::Image<OutputPixelType, Dimension> OutputImageType;

  typedef otb::ImageFileReader<InputImageType>  ReaderType;
  typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

Now, we define the types needed for the morphological filters which will be used to build the morphological pyramid. The first thing to do is define the structuring element, which in our case, will be a `itk::BinaryBallStructuringElement` which is templated over the pixel type and the dimension of the image.

```
  typedef itk::BinaryBallStructuringElement<InputPixelType, Dimension>
```

```
StructuringElementType;
```

We can now define the type of the filter to be used by the morphological pyramid. In this case, we choose to use an `otb::OpeningClosingMorphologicalFilter` which is just the concatenation of an opening and a closing. This filter is theplated over the input and output image types and the structurung element type that we just define above.

```
typedef otb::OpeningClosingMorphologicalFilter<InputImageType,
    InputImageType,
    StructuringElementType>
OpeningClosingFilterType;
```

We can now define the type of the morpholoical pyramid filter. The filter is templated over the input and output mage types and the *lowpas* morphological filter to be used.

```
typedef otb::MorphologicalPyramidAnalysisFilter<InputImageType,
    OutputImageType,
    OpeningClosingFilterType>
PyramidAnalysisFilterType;
```

We can finally define the type of the morpholoical pyramid synthesis filter. The filter is templated over the input and output mage types.

```
typedef otb::MorphologicalPyramidSynthesisFilter<InputImageType,
    OutputImageType>
PyramidSynthesisFilterType;
```

We can now instantiate the reader in order to access the input image which has to be analysed.

```
ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(inputFilename);
```

We instantiate the morphological pyramid analysis filter and set its parameters which are:

- the number of iterations or levels of the pyramid;
- the subsample scale or decimation factor between two successive pyramid levels.

After that, we plug the pipeline and run it by calling the `Update()` method.

```
PyramidAnalysisFilterType::Pointer pyramidAnalysis =
  PyramidAnalysisFilterType::New();
pyramidAnalysis->SetNumberOfLevels(numberOfLevels);
pyramidAnalysis->SetDecimationRatio(decimationRatio);
pyramidAnalysis->SetInput(reader->GetOutput());
pyramidAnalysis->Update();
```

Once the analysis step is finished we can proceed to the synthesis of the image from its different levels of decomposition. The morphological pyramid has 5 types of output:

- the Analysisd image at each level of the pyramid through the `GetOutput()` method;
- the brighter details extracted from the filtering operation through the `GetSupFilter()` method;
- the darker details extracted from the filtering operation through the `GetInfFilter()` method;
- the brighter details extracted from the resampling operation through the `GetSupDeci()` method;
- the darker details extracted from the resampling operation through the `GetInfDeci()` method; to decimation

This outputs can be used as input of the synthesis filter by using the appropriate methods.

```
PyramidSynthesisFilterType::Pointer pyramidSynthesis =
  PyramidSynthesisFilterType::New();
pyramidSynthesis->SetInput(pyramidAnalysis->GetOutput()->Back());
pyramidSynthesis->SetSupFilter(pyramidAnalysis->GetSupFilter());
pyramidSynthesis->SetSupDeci(pyramidAnalysis->GetSupDeci());
pyramidSynthesis->SetInfFilter(pyramidAnalysis->GetInfFilter());
pyramidSynthesis->SetInfDeci(pyramidAnalysis->GetInfDeci());
```

After that, we plug the pipeline and run it by calling the `Update()` method.

```
pyramidSynthesis->Update();
```

We finally instatiate a the writer in order to save the result image to a file.

```
WriterType::Pointer writer = WriterType::New();
writer->SetFileName(outputFilename);
writer->SetInput(pyramidSynthesis->GetOutput()->Back());
writer->Update();
```

Since the synthesis operation is applied on the result of the analysis, the input and the output images should be identical. This is the case as shown in figure 15.7.

Of course, in a real application, a specific processing will be applied after the analysis and before the synthesis to, for instance, denoise the image by removing pixels at the finer scales, etc.

15.2.1 Morphological Pyramid Exploitation

One of the possible uses of the morphological pyramid is the segmentation of objects – regions – of a particular scale.

The source code for this example can be found in the file
`Examples/MultiScale/MorphologicalPyramidSegmenterExample.cxx`.

Figure 15.7: Result of the morphological pyramid analysis and synthesis. Left: original image. Right: result of applying the analysis and the synthesis steps.

This example illustrates the use of the `otb::MorphologicalPyramid::Segmenter`. This class performs the segmentation of a detail image extracted from a morphological pyramid analysis. The Segmentation is perfomed using the `itk::ConnectedThresholdImageFilter`. The seeds are extracted from the image using the `otb::ImageToPointSetFilter`. The thresolds are set by using quantiles computed with the HistogramGenerator.

The first step required to use this filter is to include its header file.

```
#include "otbMorphologicalPyramidSegmenter.h"
```

As usual, we start by defining the types needed for the pixels, the images, the image reader and the image writer. Note that, for this example, an RGB image will be created to store the results of the segmentation.

```
const unsigned int Dimension = 2;
typedef double                       InputPixelType;
typedef unsigned short               LabelPixelType;
typedef itk::RGBPixel<unsigned char> RGBPixelType;

typedef otb::Image<InputPixelType, Dimension> InputImageType;
typedef otb::Image<LabelPixelType, Dimension> LabelImageType;
typedef otb::Image<RGBPixelType, 2>           RGBImageType;

typedef otb::ImageFileReader<InputImageType> ReaderType;
typedef otb::ImageFileWriter<RGBImageType>   WriterType;
```

We define now the segmenter. Please pay attention to the fact that this class belongs to the `morphologicalPyramid` namespace.

```
typedef otb::MorphologicalPyramid::Segmenter<InputImageType,
    LabelImageType>
SegmenterType;
```

We instantiate the readers which will give us access to the image of details produced by the morphological pyramid analysis and the original image (before analysis) which is used in order to produce segmented regions which are sharper than what would have been obtained with the detail image only.

```
ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(inputFilename);
ReaderType::Pointer reader2 = ReaderType::New();
reader2->SetFileName(originalFilename);
```

We instantiate the segmenter and set its parameters as follows. We plug the output of the readers for the details image and the original image; we set the boolean variable which controls wether the segmented details are bright or dark; we set the quantile used to threshold the details image in order to obtain the seed points for the segmentation; we set the quantile for setting the threshold for the region growing segmentation; and finally, we set the minimum size for a segmented region to be kept in the final result.

```
SegmenterType::Pointer segmenter = SegmenterType::New();
segmenter->SetDetailsImage(reader->GetOutput());
segmenter->SetOriginalImage(reader2->GetOutput());
segmenter->SetSegmentDarkDetailsBool(segmentDark);
segmenter->SetSeedsQuantile(seedsQuantile);
segmenter->SetConnectedThresholdQuantile(segmentationQuantile);
segmenter->SetMinimumObjectSize(minObjectSize);
```

The output of the segmenter is an image of integer labels, where a label denotes membership of a pixel in a particular segmented region. This value is usually coded using 16 bits. This format is not practical for visualization, so for the purposes of this example, we will convert it to RGB pixels. RGB images have the advantage that they can be saved as a simple png file and viewed using any standard image viewer software. The `itk::Functor::ScalarToRGBPixelFunctor` class is a special function object designed to hash a scalar value into an `itk::RGBPixel`. Plugging this functor into the `itk::UnaryFunctorImageFilter` creates an image filter for that converts scalar images to RGB images.

```
typedef itk::Functor::ScalarToRGBPixelFunctor<LabelPixelType>
ColorMapFunctorType;
typedef itk::UnaryFunctorImageFilter<LabelImageType,
    RGBImageType,
    ColorMapFunctorType> ColorMapFilterType;
ColorMapFilterType::Pointer colormapper = ColorMapFilterType::New();
```

We can now plug the final segment of the pipeline by using the color mapper and the image file writer.

```
colormapper->SetInput(segmenter->GetOutput());
WriterType::Pointer writer = WriterType::New();
writer->SetInput(colormapper->GetOutput());
writer->SetFileName(outputFilename1);
writer->Update();
```

Figure 15.8: Morphological pyramid segmentation. From left to right: original image, image of bright details and result of the sementation.

Figure 15.8 shows the results of the segmentation of the image of bright details obtained with the morphological pyramid analysis.

This same approach can be applied to all the levels of the morphological pyramid analysis.

The source code for this example can be found in the file
`Examples/MultiScale/MorphologicalPyramidSegmentationExample.cxx`.

This example illustrates the use of the `otb::MorphologicalSegmentationFilter`. This filter performs a segmentation of the details `supFilter` and `infFilter` extracted with the morphological pyramid. The segmentation algorithm used is based on seeds extraction using the `otb::ImageToPointSetFilter`, followed by a connected threshold segmentation using the `itk::ConnectedThresholdImageFilter`. The threshold for seeds extraction and segmentation are computed using quantiles. A pre processing step is applied by multiplying the full resolution brighter details (resp. darker details) with the original image (resp. the inverted original image). This perfoms an enhancement of the regions contour precision. The details from the pyramid are set via the `SetBrighterDetails()` and `SetDarkerDetails()` methods. The brighter and darker details depend on the filter used in the pyramid analysis. If the `otb::OpeningClosingMorphologicalFilter` filter is used, then the brighter details are those from the `supFilter` image list, whereas if the `otb::ClosingOpeningMorphologicalFilter` filter is used, the brighter details are those from the `infFilter` list. The output of the segmentation filter is a single segmentation images list, containing first the brighter details segmentation from higher scale to lower, and then the darker details in the same order. The attention of the user is drawn to the fact that since the label filter used internally will deal with a large number of labels, the `OutputPixelType` is required to be sufficiently precise. Unsigned short or Unsigned long would be a good choice, unless the user has a very good reason to think that a less precise type will be sufficient. The first step to use this filter is to include its header file.

```
#include "otbMorphologicalPyramidSegmentationFilter.h"
```

The mathematical morphology filters to be used have also to be included here, as well as the mor-

phological pyramid analysis filter.

```
#include "otbOpeningClosingMorphologicalFilter.h"
#include "itkBinaryBallStructuringElement.h"
#include "otbMorphologicalPyramidAnalysisFilter.h"
```

As usual, we start by defining the types for the pixels, the images, the reader and the writer. We also define the types needed for the morphological pyramid analysis.

```
const unsigned int Dimension = 2;
typedef unsigned char  InputPixelType;
typedef unsigned short OutputPixelType;

typedef otb::Image<InputPixelType, Dimension>  InputImageType;
typedef otb::Image<OutputPixelType, Dimension> OutputImageType;

typedef otb::ImageFileReader<InputImageType>  ReaderType;
typedef otb::ImageFileWriter<OutputImageType> WriterType;

typedef itk::BinaryBallStructuringElement<InputPixelType, Dimension>
StructuringElementType;
typedef otb::OpeningClosingMorphologicalFilter<InputImageType,
    InputImageType,
    StructuringElementType>
OpeningClosingFilterType;
typedef otb::MorphologicalPyramidAnalysisFilter<InputImageType,
    InputImageType,
    OpeningClosingFilterType>
PyramidFilterType;
```

We can now define the type for the `otb::MorphologicalPyramidSegmentationFilter` which is templated over the input and output image types.

```
typedef otb::MorphologicalPyramidSegmentationFilter<InputImageType,
    OutputImageType>
SegmentationFilterType;
```

Since the output of the segmentation filter is a list of images, we define an iterator type which will be used to access the segmented images.

```
typedef SegmentationFilterType::OutputImageListIteratorType
OutputListIteratorType;
```

The following code snippet shows how to read the input image and perform the morphological pyramid analysis.

```
ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(inputFilename);

PyramidFilterType::Pointer pyramid = PyramidFilterType::New();
pyramid->SetNumberOfLevels(numberOfLevels);
pyramid->SetDecimationRatio(decimationRatio);
pyramid->SetInput(reader->GetOutput());
```

We can now instantiate the segmentation filter and set its parameters. As one can see, the `SetReferenceImage()` is used to pass the original image in order to obtain sharp region boundaries. Using the `SetBrighterDetails()` and `SetDarkerDetails()` the output of the analysis is passed to the filter. Finally, the parameters for the segmentation are set by using the `SetSeedsQuantile()`, `SetConnectedThresholdQuantile()` and `SetMinimumObjectSize()` methods.

```
SegmentationFilterType::Pointer segmentation = SegmentationFilterType::New();
segmentation->SetReferenceImage(reader->GetOutput());
segmentation->SetBrighterDetails(pyramid->GetSupFilter());
segmentation->SetDarkerDetails(pyramid->GetInfFilter());
segmentation->SetSeedsQuantile(seedsQuantile);
segmentation->SetConnectedThresholdQuantile(segmentationQuantile);
segmentation->SetMinimumObjectSize(minObjectSize);
```

The pipeline is executed bu calling the `Update()` method.

```
segmentation->Update();
```

Finally, we get an iterator to the list generated as output for the segmentation and we use it to iterate through the list and write the images to files.

```
OutputListIteratorType it = segmentation->GetOutput()->Begin();
WriterType::Pointer    writer;
int                    index = 1;
std::stringstream      oss;
while (it != segmentation->GetOutput()->End())
  {
  oss << outputFilenamePrefix << index << "." << outputFilenameSuffix;
  writer = WriterType::New();
  writer->SetInput(it.Get());
  writer->SetFileName(oss.str().c_str());
  writer->Update();
  std::cout << oss.str() << " file written." << std::endl;
  oss.str("");
  ++index;
  ++it;
  }
```

The user will pay attention to the fact that the list contains first the brighter details segmentation from higher scale to lower, and then the darker details in the same order.

CHAPTER

SIXTEEN

IMAGE SEGMENTATION

Segmentation of remote sensing images is a challenging task. A myriad of different methods have been proposed and implemented in recent years. In spite of the huge effort invested in this problem, there is no single approach that can generally solve the problem of segmentation for the large variety of image modalities existing today.

The most effective segmentation algorithms are obtained by carefully customizing combinations of components. The parameters of these components are tuned for the characteristics of the image modality used as input and the features of the objects to be segmented.

The Insight Toolkit provides a basic set of algorithms that can be used to develop and customize a full segmentation application. They are therefore available in the Orfeo Toolbox. Some of the most commonly used segmentation components are described in the following sections.

16.1 Region Growing

Region growing algorithms have proven to be an effective approach for image segmentation. The basic approach of a region growing algorithm is to start from a seed region (typically one or more pixels) that are considered to be inside the object to be segmented. The pixels neighboring this region are evaluated to determine if they should also be considered part of the object. If so, they are added to the region and the process continues as long as new pixels are added to the region. Region growing algorithms vary depending on the criteria used to decide whether a pixel should be included in the region or not, the type connectivity used to determine neighbors, and the strategy used to visit neighboring pixels.

Several implementations of region growing are available in ITK. This section describes some of the most commonly used.

16.1.1 Connected Threshold

A simple criterion for including pixels in a growing region is to evaluate intensity value inside a specific interval.

The source code for this example can be found in the file
`Examples/Segmentation/ConnectedThresholdImageFilter.cxx`.

The following example illustrates the use of the `itk::ConnectedThresholdImageFilter`. This filter uses the flood fill iterator. Most of the algorithmic complexity of a region growing method comes from visiting neighboring pixels. The flood fill iterator assumes this responsibility and greatly simplifies the implementation of the region growing algorithm. Thus the algorithm is left to establish a criterion to decide whether a particular pixel should be included in the current region or not.

The criterion used by the ConnectedThresholdImageFilter is based on an interval of intensity values provided by the user. Values of lower and upper threshold should be provided. The region growing algorithm includes those pixels whose intensities are inside the interval.

$$I(\mathbf{X}) \in [\text{lower}, \text{upper}] \tag{16.1}$$

Let's look at the minimal code required to use this algorithm. First, the following header defining the ConnectedThresholdImageFilter class must be included.

```
#include "itkConnectedThresholdImageFilter.h"
```

Noise present in the image can reduce the capacity of this filter to grow large regions. When faced with noisy images, it is usually convenient to pre-process the image by using an edge-preserving smoothing filter. In this particular example we use the `itk::CurvatureFlowImageFilter`, hence we need to include its header file.

```
#include "itkCurvatureFlowImageFilter.h"
```

We declare the image type based on a particular pixel type and dimension. In this case the `float` type is used for the pixels due to the requirements of the smoothing filter.

```
typedef   float InternalPixelType;
const unsigned int Dimension = 2;
typedef otb::Image<InternalPixelType, Dimension> InternalImageType;
```

The smoothing filter is instantiated using the image type as a template parameter.

```
typedef itk::CurvatureFlowImageFilter<InternalImageType, InternalImageType>
CurvatureFlowImageFilterType;
```

Then the filter is created by invoking the `New()` method and assigning the result to a `itk::SmartPointer`.

```
CurvatureFlowImageFilterType::Pointer smoothing =
  CurvatureFlowImageFilterType::New();
```

We now declare the type of the region growing filter. In this case it is the ConnectedThresholdImageFilter.

```
typedef itk::ConnectedThresholdImageFilter<InternalImageType,
    InternalImageType>
ConnectedFilterType;
```

Then we construct one filter of this class using the `New()` method.

```
ConnectedFilterType::Pointer connectedThreshold = ConnectedFilterType::New();
```

Now it is time to connect a simple, linear pipeline. A file reader is added at the beginning of the pipeline and a cast filter and writer are added at the end. The cast filter is required to convert `float` pixel types to integer types since only a few image file formats support `float` types.

```
smoothing->SetInput(reader->GetOutput());
connectedThreshold->SetInput(smoothing->GetOutput());
caster->SetInput(connectedThreshold->GetOutput());
writer->SetInput(caster->GetOutput());
```

The CurvatureFlowImageFilter requires a couple of parameters to be defined. The following are typical values, however they may have to be adjusted depending on the amount of noise present in the input image.

```
smoothing->SetNumberOfIterations(5);
smoothing->SetTimeStep(0.125);
```

The ConnectedThresholdImageFilter has two main parameters to be defined. They are the lower and upper thresholds of the interval in which intensity values should fall in order to be included in the region. Setting these two values too close will not allow enough flexibility for the region to grow. Setting them too far apart will result in a region that engulfs the image.

```
connectedThreshold->SetLower(lowerThreshold);
connectedThreshold->SetUpper(upperThreshold);
```

The output of this filter is a binary image with zero-value pixels everywhere except on the extracted region. The intensity value set inside the region is selected with the method `SetReplaceValue()`

```
connectedThreshold->SetReplaceValue(
  itk::NumericTraits<OutputPixelType>::max());
```

The initialization of the algorithm requires the user to provide a seed point. It is convenient to select this point to be placed in a *typical* region of the structure to be segmented. The seed is passed in the form of a `itk::Index` to the `SetSeed()` method.

Structure	Seed Index	Lower	Upper	Output Image
Road	$(110, 38)$	50	100	Second from left in Figure 16.1
Shadow	$(118, 100)$	0	10	Third from left in Figure 16.1
Building	$(169, 146)$	220	255	Fourth from left in Figure 16.1

Table 16.1: Parameters used for segmenting some structures shown in Figure 16.1 with the filter `itk::ConnectedThresholdImageFilter`.

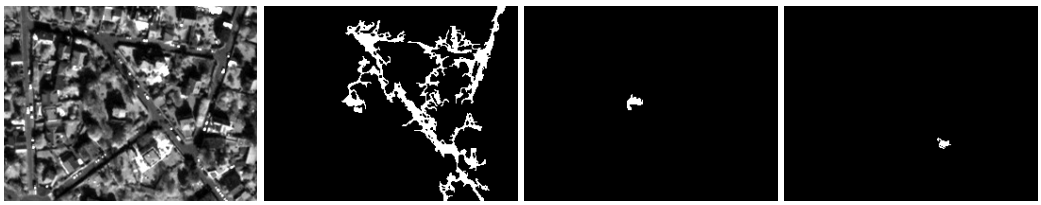


Figure 16.1: Segmentation results for the ConnectedThreshold filter for various seed points.

```
connectedThreshold->SetSeed(index);
```

The invocation of the `Update()` method on the writer triggers the execution of the pipeline. It is usually wise to put update calls in a `try/catch` block in case errors occur and exceptions are thrown.

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& excep)
  {
  std::cerr << "Exception caught !" << std::endl;
  std::cerr << excep << std::endl;
  }
```

Let's run this example using as input the image `QB_Suburb.png` provided in the directory `Examples/Data`. We can easily segment the major structures by providing seeds in the appropriate locations and defining values for the lower and upper thresholds. Figure 16.1 illustrates several examples of segmentation. The parameters used are presented in Table 16.1.

Notice that some objects are not being completely segmented. This illustrates the vulnerability of the region growing methods when the structures to be segmented do not have a homogeneous statistical distribution over the image space. You may want to experiment with different values of the lower and upper thresholds to verify how the accepted region will extend.

Another option for segmenting regions is to take advantage of the functionality provided by the ConnectedThresholdImageFilter for managing multiple seeds. The seeds can be passed one by one to the filter using the `AddSeed()` method. You could imagine a user interface in which an operator

clicks on multiple points of the object to be segmented and each selected point is passed as a seed to this filter.

16.1.2 Otsu Segmentation

Another criterion for classifying pixels is to minimize the error of misclassification. The goal is to find a threshold that classifies the image into two clusters such that we minimize the area under the histogram for one cluster that lies on the other cluster's side of the threshold. This is equivalent to minimizing the within class variance or equivalently maximizing the between class variance.

The source code for this example can be found in the file `Examples/Segmentation/OtsuThresholdImageFilter.cxx`.

This example illustrates how to use the `itk::OtsuThresholdImageFilter`.

```
#include "itkOtsuThresholdImageFilter.h"
```

The next step is to decide which pixel types to use for the input and output images.

```
typedef  unsigned char InputPixelType;
typedef  unsigned char OutputPixelType;
```

The input and output image types are now defined using their respective pixel types and dimensions.

```
typedef otb::Image<InputPixelType,  2> InputImageType;
typedef otb::Image<OutputPixelType, 2> OutputImageType;
```

The filter type can be instantiated using the input and output image types defined above.

```
typedef itk::OtsuThresholdImageFilter<
    InputImageType, OutputImageType>  FilterType;
```

An `otb::ImageFileReader` class is also instantiated in order to read image data from a file. (See Section 6 on page 97 for more information about reading and writing data.)

```
typedef otb::ImageFileReader<InputImageType> ReaderType;
```

An `otb::ImageFileWriter` is instantiated in order to write the output image to a file.

```
typedef otb::ImageFileWriter<InputImageType> WriterType;
```

Both the filter and the reader are created by invoking their `New()` methods and assigning the result to `itk::SmartPointer`s.

```
ReaderType::Pointer reader = ReaderType::New();
FilterType::Pointer filter = FilterType::New();
```

The image obtained with the reader is passed as input to the OtsuThresholdImageFilter.

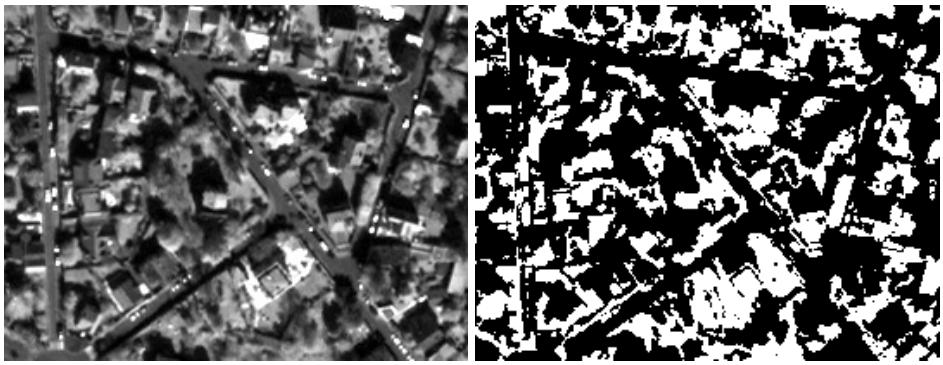


Figure 16.2: Effect of the OtsuThresholdImageFilter.

```
filter->SetInput(reader->GetOutput());
```

The method `SetOutsideValue()` defines the intensity value to be assigned to those pixels whose intensities are outside the range defined by the lower and upper thresholds. The method `SetInsideValue()` defines the intensity value to be assigned to pixels with intensities falling inside the threshold range.

```
filter->SetOutsideValue(outsideValue);
filter->SetInsideValue(insideValue);
```

The method `SetNumberOfHistogramBins()` defines the number of bins to be used for computing the histogram. This histogram will be used internally in order to compute the Otsu threshold.

```
filter->SetNumberOfHistogramBins(128);
```

The execution of the filter is triggered by invoking the `Update()` method. If the filter's output has been passed as input to subsequent filters, the `Update()` call on any posterior filters in the pipeline will indirectly trigger the update of this filter.

```
filter->Update();
```

We print out here the Threshold value that was computed internally by the filter. For this we invoke the `GetThreshold` method.

```
int threshold = filter->GetThreshold();
std::cout << "Threshold = " << threshold << std::endl;
```

Figure 16.2 illustrates the effect of this filter. This figure shows the limitations of this filter for performing segmentation by itself. These limitations are particularly noticeable in noisy images and in images lacking spatial uniformity.

The following classes provide similar functionality:

- itk::ThresholdImageFilter

The source code for this example can be found in the file
Examples/Segmentation/OtsuMultipleThresholdImageFilter.cxx.

This example illustrates how to use the itk::OtsuMultipleThresholdsCalculator.

```
#include "itkOtsuMultipleThresholdsCalculator.h"
```

OtsuMultipleThresholdsCalculator calculates thresholds for a give histogram so as to maximize the between-class variance. We use ScalarImageToHistogramGenerator to generate histograms

```
typedef itk::Statistics::ScalarImageToHistogramGenerator<InputImageType>
ScalarImageToHistogramGeneratorType;
typedef itk::OtsuMultipleThresholdsCalculator<
    ScalarImageToHistogramGeneratorType::HistogramType>   CalculatorType;
```

Once thresholds are computed we will use BinaryThresholdImageFilter to segment the input image into segments.

```
typedef itk::BinaryThresholdImageFilter<InputImageType, OutputImageType>
FilterType;
```

```
ScalarImageToHistogramGeneratorType::Pointer scalarImageToHistogramGenerator
  =
    ScalarImageToHistogramGeneratorType::New();
CalculatorType::Pointer calculator = CalculatorType::New();
FilterType::Pointer     filter = FilterType::New();
```

```
scalarImageToHistogramGenerator->SetNumberOfBins(128);
int nbThresholds = argc - 2;
calculator->SetNumberOfThresholds(nbThresholds);
```

The pipeline will look as follows:

```
scalarImageToHistogramGenerator->SetInput(reader->GetOutput());
calculator->SetInputHistogram(scalarImageToHistogramGenerator->GetOutput());
filter->SetInput(reader->GetOutput());
writer->SetInput(filter->GetOutput());
```

Thresholds are obtained using the GetOutput method

```
const CalculatorType::OutputType& thresholdVector =
  calculator->GetOutput();
CalculatorType::OutputType::const_iterator itNum = thresholdVector.begin();
```

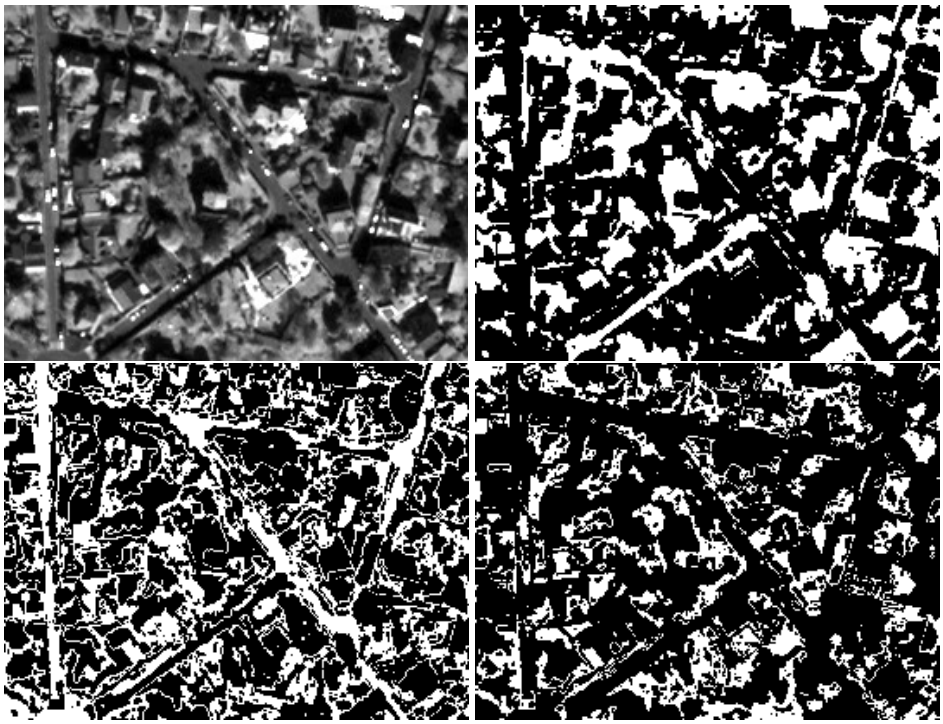


Figure 16.3: Effect of the OtsuMultipleThresholdImageFilter.

```
for (; itNum < thresholdVector.end(); itNum++)
  {
  std::cout << "OtsuThreshold["
            << (int) (itNum - thresholdVector.begin())
            << "] = " <<
  static_cast<itk::NumericTraits<CalculatorType::MeasurementType>::PrintType>
  (*itNum) << std::endl;

  upperThreshold = (*itNum);
  filter->SetLowerThreshold(static_cast<OutputPixelType> (lowerThreshold));
  filter->SetUpperThreshold(static_cast<OutputPixelType> (upperThreshold));
  lowerThreshold = upperThreshold;

  writer->SetFileName(argv[2 + counter]);
  ++counter;
```

```
  }
```

Figure 16.3 illustrates the effect of this filter.

The following classes provide similar functionality:

- itk::ThresholdImageFilter

16.1.3 Neighborhood Connected

The source code for this example can be found in the file
Examples/Segmentation/NeighborhoodConnectedImageFilter.cxx.

The following example illustrates the use of the itk::NeighborhoodConnectedImageFilter. This filter is a close variant of the itk::ConnectedThresholdImageFilter. On one hand, the ConnectedThresholdImageFilter accepts a pixel in the region if its intensity is in the interval defined by two user-provided threshold values. The NeighborhoodConnectedImageFilter, on the other hand, will only accept a pixel if **all** its neighbors have intensities that fit in the interval. The size of the neighborhood to be considered around each pixel is defined by a user-provided integer radius.

The reason for considering the neighborhood intensities instead of only the current pixel intensity is that small structures are less likely to be accepted in the region. The operation of this filter is equivalent to applying the ConnectedThresholdImageFilter followed by mathematical morphology erosion using a structuring element of the same shape as the neighborhood provided to the NeighborhoodConnectedImageFilter.

```
#include "itkNeighborhoodConnectedImageFilter.h"
```

The itk::CurvatureFlowImageFilter is used here to smooth the image while preserving edges.

```
#include "itkCurvatureFlowImageFilter.h"
```

We now define the image type using a particular pixel type and image dimension. In this case the float type is used for the pixels due to the requirements of the smoothing filter.

```
typedef   float InternalPixelType;
const unsigned int Dimension = 2;
typedef otb::Image<InternalPixelType, Dimension> InternalImageType;
```

The smoothing filter type is instantiated using the image type as a template parameter.

```
typedef   itk::CurvatureFlowImageFilter<InternalImageType, InternalImageType>
CurvatureFlowImageFilterType;
```

Then, the filter is created by invoking the New() method and assigning the result to a itk::SmartPointer.

```
CurvatureFlowImageFilterType::Pointer smoothing =
  CurvatureFlowImageFilterType::New();
```

We now declare the type of the region growing filter. In this case it is the NeighborhoodConnectedImageFilter.

```
typedef itk::NeighborhoodConnectedImageFilter<InternalImageType,
    InternalImageType>
ConnectedFilterType;
```

One filter of this class is constructed using the `New()` method.

```
ConnectedFilterType::Pointer neighborhoodConnected = ConnectedFilterType::New();
```

Now it is time to create a simple, linear data processing pipeline. A file reader is added at the beginning of the pipeline and a cast filter and writer are added at the end. The cast filter is required to convert `float` pixel types to integer types since only a few image file formats support `float` types.

```
smoothing->SetInput(reader->GetOutput());
neighborhoodConnected->SetInput(smoothing->GetOutput());
caster->SetInput(neighborhoodConnected->GetOutput());
writer->SetInput(caster->GetOutput());
```

The CurvatureFlowImageFilter requires a couple of parameters to be defined. The following are typical values for $2D$ images. However they may have to be adjusted depending on the amount of noise present in the input image.

```
smoothing->SetNumberOfIterations(5);
smoothing->SetTimeStep(0.125);
```

The NeighborhoodConnectedImageFilter requires that two main parameters are specified. They are the lower and upper thresholds of the interval in which intensity values must fall to be included in the region. Setting these two values too close will not allow enough flexibility for the region to grow. Setting them too far apart will result in a region that engulfs the image.

```
neighborhoodConnected->SetLower(lowerThreshold);
neighborhoodConnected->SetUpper(upperThreshold);
```

Here, we add the crucial parameter that defines the neighborhood size used to determine whether a pixel lies in the region. The larger the neighborhood, the more stable this filter will be against noise in the input image, but also the longer the computing time will be. Here we select a filter of radius 2 along each dimension. This results in a neighborhood of 5×5 pixels.

```
InternalImageType::SizeType radius;

radius[0] = 2;   // two pixels along X
radius[1] = 2;   // two pixels along Y

neighborhoodConnected->SetRadius(radius);
```

As in the ConnectedThresholdImageFilter we must now provide the intensity value to be used for the output pixels accepted in the region and at least one seed point to define the initial region.

Structure	Seed Index	Lower	Upper	Output Image
Road	$(110,38)$	50	100	Second from left in Figure 16.4
Shadow	$(118,100)$	0	10	Third from left in Figure 16.4
Building	$(169,146)$	220	255	Fourth from left in Figure 16.4

Table 16.2: Parameters used for segmenting some structures shown in Figure 16.4 with the filter `itk::NeighborhoodConnectedThresholdImageFilter`.

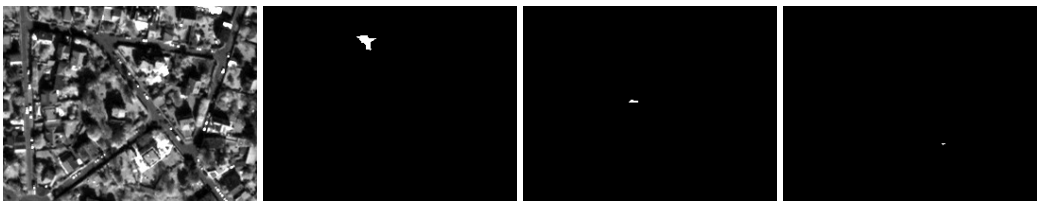


Figure 16.4: Segmentation results for the NeighborhoodConnectedThreshold filter for various seed points.

```
neighborhoodConnected->SetSeed(index);
neighborhoodConnected->SetReplaceValue(255);
```

The invocation of the `Update()` method on the writer triggers the execution of the pipeline. It is usually wise to put update calls in a `try/catch` block in case errors occur and exceptions are thrown.

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& excep)
  {
  std::cerr << "Exception caught !" << std::endl;
  std::cerr << excep << std::endl;
  }
```

Let's run this example using as input the image `QB_Suburb.png` provided in the directory `Examples/Data`. We can easily segment the major structures by providing seeds in the appropriate locations and defining values for the lower and upper thresholds. Figure 16.4 illustrates several examples of segmentation. The parameters used are presented in Table 16.2.

As with the ConnectedThresholdImageFilter, several seeds could be provided to the filter by using the `AddSeed()` method. Compare the output of Figure 16.4 with those of Figure 16.1 produced by the ConnectedThresholdImageFilter. You may want to play with the value of the neighborhood radius and see how it affect the smoothness of the segmented object borders, the size of the segmented region and how much that costs in computing time.

16.1.4 Confidence Connected

The source code for this example can be found in the file
`Examples/Segmentation/ConfidenceConnected.cxx`.

The following example illustrates the use of the `itk::ConfidenceConnectedImageFilter`. The criterion used by the ConfidenceConnectedImageFilter is based on simple statistics of the current region. First, the algorithm computes the mean and standard deviation of intensity values for all the pixels currently included in the region. A user-provided factor is used to multiply the standard deviation and define a range around the mean. Neighbor pixels whose intensity values fall inside the range are accepted and included in the region. When no more neighbor pixels are found that satisfy the criterion, the algorithm is considered to have finished its first iteration. At that point, the mean and standard deviation of the intensity levels are recomputed using all the pixels currently included in the region. This mean and standard deviation defines a new intensity range that is used to visit current region neighbors and evaluate whether their intensity falls inside the range. This iterative process is repeated until no more pixels are added or the maximum number of iterations is reached. The following equation illustrates the inclusion criterion used by this filter,

$$I(\mathbf{X}) \in [m - f\sigma, m + f\sigma] \tag{16.2}$$

where m and σ are the mean and standard deviation of the region intensities, f is a factor defined by the user, $I()$ is the image and $\mathbf{X}$ is the position of the particular neighbor pixel being considered for inclusion in the region.

Let's look at the minimal code required to use this algorithm. First, the following header defining the `itk::ConfidenceConnectedImageFilter` class must be included.

```
#include "itkConfidenceConnectedImageFilter.h"
```

Noise present in the image can reduce the capacity of this filter to grow large regions. When faced with noisy images, it is usually convenient to pre-process the image by using an edge-preserving smoothing filter. In this particular example we use the `itk::CurvatureFlowImageFilter`, hence we need to include its header file.

```
#include "itkCurvatureFlowImageFilter.h"
```

We now define the image type using a pixel type and a particular dimension. In this case the `float` type is used for the pixels due to the requirements of the smoothing filter.

```
typedef   float InternalPixelType;
const unsigned int Dimension = 2;
typedef otb::Image<InternalPixelType, Dimension> InternalImageType;
```

The smoothing filter type is instantiated using the image type as a template parameter.

```
typedef itk::CurvatureFlowImageFilter<InternalImageType, InternalImageType>
CurvatureFlowImageFilterType;
```

Next the filter is created by invoking the `New()` method and assigning the result to a `itk::SmartPointer`.

```
CurvatureFlowImageFilterType::Pointer smoothing =
  CurvatureFlowImageFilterType::New();
```

We now declare the type of the region growing filter. In this case it is the ConfidenceConnectedImageFilter.

```
typedef itk::ConfidenceConnectedImageFilter<InternalImageType,
    InternalImageType>
ConnectedFilterType;
```

Then, we construct one filter of this class using the `New()` method.

```
ConnectedFilterType::Pointer confidenceConnected = ConnectedFilterType::New();
```

Now it is time to create a simple, linear pipeline. A file reader is added at the beginning of the pipeline and a cast filter and writer are added at the end. The cast filter is required here to convert `float` pixel types to integer types since only a few image file formats support `float` types.

```
smoothing->SetInput(reader->GetOutput());
confidenceConnected->SetInput(smoothing->GetOutput());
caster->SetInput(confidenceConnected->GetOutput());
writer->SetInput(caster->GetOutput());
```

The CurvatureFlowImageFilter requires defining two parameters. The following are typical values. However they may have to be adjusted depending on the amount of noise present in the input image.

```
smoothing->SetNumberOfIterations(5);
smoothing->SetTimeStep(0.125);
```

The ConfidenceConnectedImageFilter requires defining two parameters. First, the factor f that the defines how large the range of intensities will be. Small values of the multiplier will restrict the inclusion of pixels to those having very similar intensities to those in the current region. Larger values of the multiplier will relax the accepting condition and will result in more generous growth of the region. Values that are too large will cause the region to grow into neighboring regions that may actually belong to separate structures.

```
confidenceConnected->SetMultiplier(2.5);
```

The number of iterations is specified based on the homogeneity of the intensities of the object to be segmented. Highly homogeneous regions may only require a couple of iterations. Regions with ramp effect, may require more iterations. In practice, it seems to be more important to carefully select the multiplier factor than the number of iterations. However, keep in mind that there is no reason to assume that this algorithm should converge to a stable region. It is possible that by letting the algorithm run for more iterations the region will end up engulfing the entire image.

```
confidenceConnected->SetNumberOfIterations(5);
```

The output of this filter is a binary image with zero-value pixels everywhere except on the extracted region. The intensity value to be set inside the region is selected with the method `SetReplaceValue()`

```
confidenceConnected->SetReplaceValue(255);
```

The initialization of the algorithm requires the user to provide a seed point. It is convenient to select this point to be placed in a *typical* region of the structure to be segmented. A small neighborhood around the seed point will be used to compute the initial mean and standard deviation for the inclusion criterion. The seed is passed in the form of a `itk::Index` to the `SetSeed()` method.

```
confidenceConnected->SetSeed(index);
```

The size of the initial neighborhood around the seed is defined with the method `SetInitialNeighborhoodRadius()`. The neighborhood will be defined as an N-dimensional rectangular region with $2r+1$ pixels on the side, where r is the value passed as initial neighborhood radius.

```
confidenceConnected->SetInitialNeighborhoodRadius(2);
```

The invocation of the `Update()` method on the writer triggers the execution of the pipeline. It is recommended to place update calls in a `try/catch` block in case errors occur and exceptions are thrown.

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& excep)
  {
  std::cerr << "Exception caught !" << std::endl;
  std::cerr << excep << std::endl;
  }
```

Let's now run this example using as input the image `QB_Suburb.png` provided in the directory `Examples/Data`. We can easily segment structures by providing seeds in the appropriate locations. For example

Structure	Seed Index	Lower	Upper	Output Image
Road	$(110,38)$	50	100	Second from left in Figure 16.1
Shadow	$(118,100)$	0	10	Third from left in Figure 16.1
Building	$(169,146)$	220	255	Fourth from left in Figure 16.1

Table 16.3: Parameters used for segmenting some structures shown in Figure 16.1 with the filter `itk::ConnectedThresholdImageFilter`.

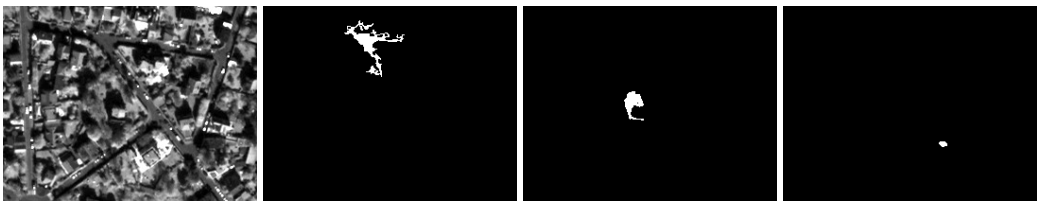


Figure 16.5: Segmentation results for the ConfidenceConnected filter for various seed points.

16.2 Segmentation Based on Watersheds

16.2.1 Overview

Watershed segmentation classifies pixels into regions using gradient descent on image features and analysis of weak points along region boundaries. Imagine water raining onto a landscape topology and flowing with gravity to collect in low basins. The size of those basins will grow with increasing amounts of precipitation until they spill into one another, causing small basins to merge together into larger basins. Regions (catchment basins) are formed by using local geometric structure to associate points in the image domain with local extrema in some feature measurement such as curvature or gradient magnitude. This technique is less sensitive to user-defined thresholds than classic region-growing methods, and may be better suited for fusing different types of features from different data sets. The watersheds technique is also more flexible in that it does not produce a single image segmentation, but rather a hierarchy of segmentations from which a single region or set of regions can be extracted a-priori, using a threshold, or interactively, with the help of a graphical user interface [147, 148].

The strategy of watershed segmentation is to treat an image f as a height function, i.e., the surface formed by graphing f as a function of its independent parameters, $\vec{x} \in U$. The image f is often not the original input data, but is derived from that data through some filtering, graded (or fuzzy) feature extraction, or fusion of feature maps from different sources. The assumption is that higher values of f (or $-f$) indicate the presence of boundaries in the original data. Watersheds may therefore be considered as a final or intermediate step in a hybrid segmentation method, where the initial segmentation is the generation of the edge feature map.

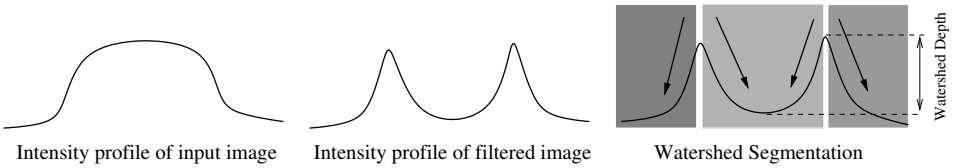


Figure 16.6: A fuzzy-valued boundary map, from an image or set of images, is segmented using local minima and catchment basins.

Gradient descent associates regions with local minima of f (clearly interior points) using the watersheds of the graph of f, as in Figure 16.6. That is, a segment consists of all points in U whose paths of steepest descent on the graph of f terminate at the same minimum in f. Thus, there are as many segments in an image as there are minima in f. The segment boundaries are "ridges" [79, 80, 44] in the graph of f. In the 1D case ($U \subset \Re$), the watershed boundaries are the local maxima of f, and the results of the watershed segmentation is trivial. For higher-dimensional image domains, the watershed boundaries are not simply local phenomena; they depend on the shape of the entire watershed.

The drawback of watershed segmentation is that it produces a region for each local minimum—in practice too many regions—and an over segmentation results. To alleviate this, we can establish a minimum watershed depth. The watershed depth is the difference in height between the watershed minimum and the lowest boundary point. In other words, it is the maximum depth of water a region could hold without flowing into any of its neighbors. Thus, a watershed segmentation algorithm can sequentially combine watersheds whose depths fall below the minimum until all of the watersheds are of sufficient depth. This depth measurement can be combined with other saliency measurements, such as size. The result is a segmentation containing regions whose boundaries and size are significant. Because the merging process is sequential, it produces a hierarchy of regions, as shown in Figure 16.7. Previous work has shown the benefit of a user-assisted approach that provides a graphical interface to this hierarchy, so that a technician can quickly move from the small regions that lie within an area of interest to the union of regions that correspond to the anatomical structure [148].

There are two different algorithms commonly used to implement watersheds: top-down and bottom-up. The top-down, gradient descent strategy was chosen for ITK because we want to consider the output of multi-scale differential operators, and the f in question will therefore have floating point values. The bottom-up strategy starts with seeds at the local minima in the image and grows regions outward and upward at discrete intensity levels (equivalent to a sequence of morphological operations and sometimes called *morphological watersheds* [123].) This limits the accuracy by enforcing a set of discrete gray levels on the image.

Figure 16.8 shows how the ITK image-to-image watersheds filter is constructed. The filter is actually a collection of smaller filters that modularize the several steps of the algorithm in a mini-pipeline. The segmenter object creates the initial segmentation via steepest descent from each pixel to local minima. Shallow background regions are removed (flattened) before segmentation using a simple minimum value threshold (this helps to minimize oversegmentation of the image). The initial seg-

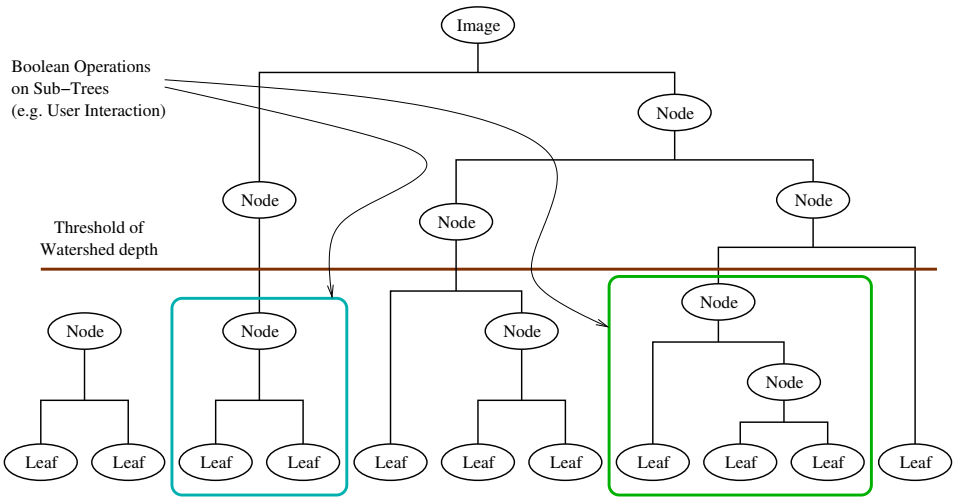


Figure 16.7: A watershed segmentation combined with a saliency measure (watershed depth) produces a hierarchy of regions. Structures can be derived from images by either thresholding the saliency measure or combining subtrees within the hierarchy.

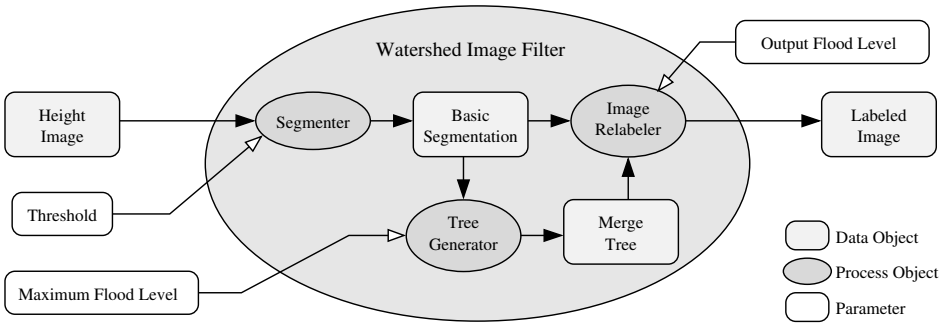


Figure 16.8: The construction of the Insight watersheds filter.

mentation is passed to a second sub-filter that generates a hierarchy of basins to a user-specified maximum watershed depth. The relabeler object at the end of the mini-pipeline uses the hierarchy and the initial segmentation to produce an output image at any scale *below* the user-specified maximum. Data objects are cached in the mini-pipeline so that changing watershed depths only requires a (fast) relabeling of the basic segmentation. The three parameters that control the filter are shown in Figure 16.8 connected to their relevant processing stages.

16.2.2 Using the ITK Watershed Filter

The source code for this example can be found in the file
`Examples/Segmentation/WatershedSegmentation.cxx`.

The following example illustrates how to preprocess and segment images using the `itk::WatershedImageFilter`. Note that the care with which the data is preprocessed will greatly affect the quality of your result. Typically, the best results are obtained by preprocessing the original image with an edge-preserving diffusion filter, such as one of the anisotropic diffusion filters, or with the bilateral image filter. As noted in Section 16.2.1, the height function used as input should be created such that higher positive values correspond to object boundaries. A suitable height function for many applications can be generated as the gradient magnitude of the image to be segmented.

The `itk::VectorGradientMagnitudeAnisotropicDiffusionImageFilter` class is used to smooth the image and the `itk::VectorGradientMagnitudeImageFilter` is used to generate the height function. We begin by including all preprocessing filter header files and the header file for the WatershedImageFilter. We use the vector versions of these filters because the input data is a color image.

```
#include "itkVectorGradientAnisotropicDiffusionImageFilter.h"
#include "itkVectorGradientMagnitudeImageFilter.h"
#include "itkWatershedImageFilter.h"
```

We now declare the image and pixel types to use for instantiation of the filters. All of these filters expect real-valued pixel types in order to work properly. The preprocessing stages are done directly on the vector-valued data and the segmentation is done using floating point scalar data. Images are converted from RGB pixel type to numerical vector type using `itk::VectorCastImageFilter`. Please pay attention to the fact that we are using `itk::Images` since the `itk::VectorGradientMagnitudeImageFilter` has some internal typedefs which make polymorfism impossible.

```
  typedef itk::RGBPixel<unsigned char>   RGBPixelType;
  typedef otb::Image<RGBPixelType, 2>    RGBImageType;
  typedef itk::Vector<float, 3>          VectorPixelType;
  typedef itk::Image<VectorPixelType, 2> VectorImageType;
  typedef itk::Image<unsigned long, 2>   LabeledImageType;
  typedef itk::Image<float, 2>           ScalarImageType;
```

The various image processing filters are declared using the types created above and eventually used in the pipeline.

```
typedef otb::ImageFileReader<RGBImageType> FileReaderType;
typedef itk::VectorCastImageFilter<RGBImageType, VectorImageType>
CastFilterType;
typedef itk::VectorGradientAnisotropicDiffusionImageFilter<VectorImageType,
    VectorImageType>
DiffusionFilterType;
typedef itk::VectorGradientMagnitudeImageFilter<VectorImageType, float,
    ScalarImageType>
GradientMagnitudeFilterType;
typedef itk::WatershedImageFilter<ScalarImageType> WatershedFilterType;
```

Next we instantiate the filters and set their parameters. The first step in the image processing pipeline is diffusion of the color input image using an anisotropic diffusion filter. For this class of filters, the CFL condition requires that the time step be no more than 0.25 for two-dimensional images, and no more than 0.125 for three-dimensional images. The number of iterations and the conductance term will be taken from the command line. See Section 8.7.2 for more information on the ITK anisotropic diffusion filters.

```
DiffusionFilterType::Pointer diffusion = DiffusionFilterType::New();
diffusion->SetNumberOfIterations(atoi(argv[4]));
diffusion->SetConductanceParameter(atof(argv[3]));
diffusion->SetTimeStep(0.125);
diffusion->SetUseImageSpacing(false);
```

The ITK gradient magnitude filter for vector-valued images can optionally take several parameters. Here we allow only enabling or disabling of principal component analysis.

```
GradientMagnitudeFilterType::Pointer
  gradient = GradientMagnitudeFilterType::New();
gradient->SetUsePrincipleComponents(atoi(argv[7]));
gradient->SetUseImageSpacingOff();
```

Finally we set up the watershed filter. There are two parameters. `Level` controls watershed depth, and `Threshold` controls the lower thresholding of the input. Both parameters are set as a percentage (0.0 - 1.0) of the maximum depth in the input image.

```
WatershedFilterType::Pointer watershed = WatershedFilterType::New();
watershed->SetLevel(atof(argv[6]));
watershed->SetThreshold(atof(argv[5]));
```

The output of WatershedImageFilter is an image of unsigned long integer labels, where a label denotes membership of a pixel in a particular segmented region. This format is not practical for visualization, so for the purposes of this example, we will convert it to RGB pixels. RGB images have the advantage that they can be saved as a simple png file and viewed using any standard image viewer software. The `itk::Functor::ScalarToRGBPixelFunctor` class is a special function object designed to hash a scalar value into an `itk::RGBPixel`. Plugging this functor into the `itk::UnaryFunctorImageFilter` creates an image filter for that converts scalar images to RGB images.

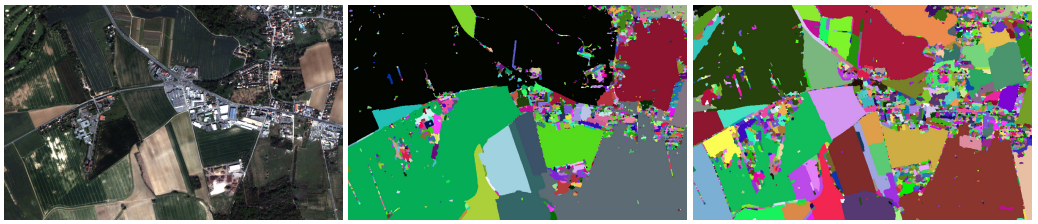


Figure 16.9: Segmented RGB image. At left is the original image. The image in the middle was generated with parameters: conductance = 2.0, iterations = 10, threshold = 0.0, level = 0.05, principal components = on. The image on the right was generated with parameters: conductance = 2.0, iterations = 10, threshold = 0.001, level = 0.15, principal components = off.

```
typedef itk::Functor::ScalarToRGBPixelFunctor<unsigned long>
ColorMapFunctorType;
typedef itk::UnaryFunctorImageFilter<LabeledImageType,
    RGBImageType,
    ColorMapFunctorType> ColorMapFilterType;
ColorMapFilterType::Pointer colormapper = ColorMapFilterType::New();
```

The filters are connected into a single pipeline, with readers and writers at each end.

```
caster->SetInput(reader->GetOutput());
diffusion->SetInput(caster->GetOutput());
gradient->SetInput(diffusion->GetOutput());
watershed->SetInput(gradient->GetOutput());
colormapper->SetInput(watershed->GetOutput());
writer->SetInput(colormapper->GetOutput());
```

Tuning the filter parameters for any particular application is a process of trial and error. The *threshold* parameter can be used to great effect in controlling oversegmentation of the image. Raising the threshold will generally reduce computation time and produce output with fewer and larger regions. The trick in tuning parameters is to consider the scale level of the objects that you are trying to segment in the image. The best time/quality trade-off will be achieved when the image is smoothed and thresholded to eliminate features just below the desired scale.

Figure 16.9 shows output from the example code. Note that a critical difference between the two segmentations is the mode of the gradient magnitude calculation.

A note on the computational complexity of the watershed algorithm is warranted. Most of the complexity of the ITK implementation lies in generating the hierarchy. Processing times for this stage are non-linear with respect to the number of catchment basins in the initial segmentation. This means that the amount of information contained in an image is more significant than the number of pixels in the image. A very large, but very flat input take less time to segment than a very small, but very detailed input.

16.3 Level Set Segmentation

The paradigm of the level set is that it is a numerical method for tracking the evolution of contours and surfaces. Instead of manipulating the contour directly, the contour is embedded as the zero level set of a higher dimensional function called the level-set function, $\psi(\mathbf{X},\mathbf{t})$. The level-set function is then evolved under the control of a differential equation. At any time, the evolving contour can be obtained by extracting the zero level-set $\Gamma((\mathbf{X}),\mathbf{t}) = \{\psi(\mathbf{X},\mathbf{t}) = \mathbf{0}\}$ from the output. The main advantages of using level sets is that arbitrarily complex shapes can be modeled and topological changes such as merging and splitting are handled implicitly.

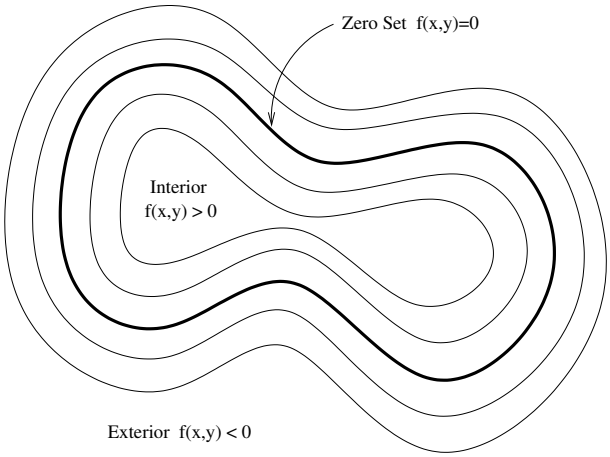


Figure 16.10: Concept of zero set in a level set.

Level sets can be used for image segmentation by using image-based features such as mean intensity, gradient and edges in the governing differential equation. In a typical approach, a contour is initialized by a user and is then evolved until it fits the form of an object in the image. Many different implementations and variants of this basic concept have been published in the literature. An overview of the field has been made by Sethian [124].

The following sections introduce practical examples of some of the level set segmentation methods available in ITK. The remainder of this section describes features common to all of these filters except the `itk::FastMarchingImageFilter`, which is derived from a different code framework. Understanding these features will aid in using the filters more effectively.

Each filter makes use of a generic level-set equation to compute the update to the solution ψ of the partial differential equation.

$$\frac{d}{dt}\psi = -\alpha\mathbf{A}(\mathbf{x})\cdot\nabla\psi - \beta P(\mathbf{x}) \mid \nabla\psi \mid + \gamma Z(\mathbf{x})\kappa \mid \nabla\psi \mid \tag{16.3}$$

where $\mathbf{A}$ is an advection term, P is a propagation (expansion) term, and Z is a spatial modifier term for the mean curvature κ. The scalar constants α, β, and γ weight the relative influence of each of the terms on the movement of the interface. A segmentation filter may use all of these terms in its calculations, or it may omit one or more terms. If a term is left out of the equation, then setting the corresponding scalar constant weighting will have no effect.

All of the level-set based segmentation filters *must* operate with floating point precision to produce

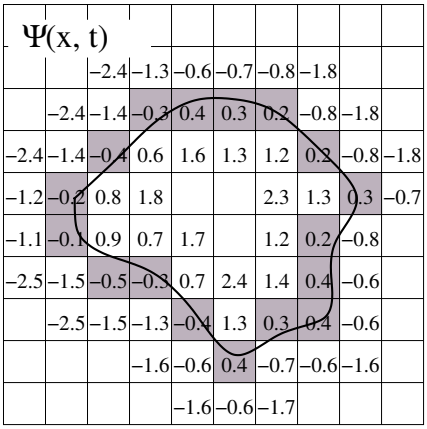


Figure 16.11: The implicit level set surface Γ is the black line superimposed over the image grid. The location of the surface is interpolated by the image pixel values. The grid pixels closest to the implicit surface are shown in gray.

valid results. The third, optional template parameter is the *numerical type* used for calculations and as the output image pixel type. The numerical type is `float` by default, but can be changed to `double` for extra precision. A user-defined, signed floating point type that defines all of the necessary arithmetic operators and has sufficient precision is also a valid choice. You should not use types such as `int` or `unsigned char` for the numerical parameter. If the input image pixel types do not match the numerical type, those inputs will be cast to an image of appropriate type when the filter is executed.

Most filters require two images as input, an initial model $\psi(\mathbf{X}, \mathbf{t} = \mathbf{0})$, and a *feature image*, which is either the image you wish to segment or some preprocessed version. You must specify the isovalue that represents the surface Γ in your initial model. The single image output of each filter is the function ψ at the final time step. It is important to note that the contour representing the surface Γ is the zero level-set of the output image, and not the isovalue you specified for the initial model. To represent Γ using the original isovalue, simply add that value back to the output.

The solution Γ is calculated to subpixel precision. The best discrete approximation of the surface is therefore the set of grid positions closest to the zero-crossings in the image, as shown in Figure 16.11. The `itk::ZeroCrossingImageFilter` operates by finding exactly those grid positions and can be used to extract the surface.

There are two important considerations when analyzing the processing time for any particular level-set segmentation task: the surface area of the evolving interface and the total distance that the surface must travel. Because the level-set equations are usually solved only at pixels near the surface (fast marching methods are an exception), the time taken at each iteration depends on the number of points on the surface. This means that as the surface grows, the solver will slow down proportionally. Because the surface must evolve slowly to prevent numerical instabilities in the solution, the distance

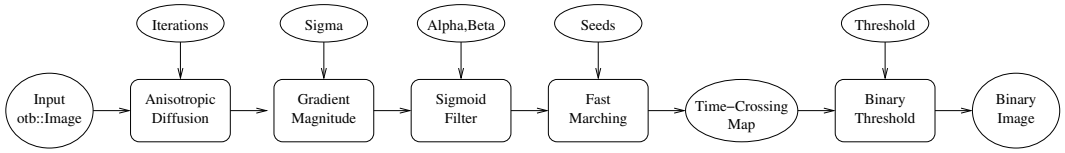


Figure 16.12: Collaboration diagram of the FastMarchingImageFilter applied to a segmentation task.

the surface must travel in the image dictates the total number of iterations required.

Some level-set techniques are relatively insensitive to initial conditions and are therefore suitable for region-growing segmentation. Other techniques, such as the `itk::LaplacianSegmentationLevelSetImageFilter`, can easily become "stuck" on image features close to their initialization and should be used only when a reasonable prior segmentation is available as the initialization. For best efficiency, your initial model of the surface should be the best guess possible for the solution.

16.3.1 Fast Marching Segmentation

The source code for this example can be found in the file
`Examples/Segmentation/FastMarchingImageFilter.cxx`.

When the differential equation governing the level set evolution has a very simple form, a fast evolution algorithm called fast marching can be used.

The following example illustrates the use of the `itk::FastMarchingImageFilter`. This filter implements a fast marching solution to a simple level set evolution problem. In this example, the speed term used in the differential equation is expected to be provided by the user in the form of an image. This image is typically computed as a function of the gradient magnitude. Several mappings are popular in the literature, for example, the negative exponential $exp(-x)$ and the reciprocal $1/(1+x)$. In the current example we decided to use a Sigmoid function since it offers a good deal of control parameters that can be customized to shape a nice speed image.

The mapping should be done in such a way that the propagation speed of the front will be very low close to high image gradients while it will move rather fast in low gradient areas. This arrangement will make the contour propagate until it reaches the edges of anatomical structures in the image and then slow down in front of those edges. The output of the FastMarchingImageFilter is a *time-crossing map* that indicates, for each pixel, how much time it would take for the front to arrive at the pixel location.

The application of a threshold in the output image is then equivalent to taking a snapshot of the contour at a particular time during its evolution. It is expected that the contour will take a longer time to cross over the edges of a particular structure. This should result in large changes on the time-crossing map values close to the structure edges. Segmentation is performed with this filter by locating a time range in which the contour was contained for a long time in a region of the image

space.

Figure 16.12 shows the major components involved in the application of the FastMarchingImageFilter to a segmentation task. It involves an initial stage of smoothing using the itk::CurvatureAnisotropicDiffusionImageFilter. The smoothed image is passed as the input to the itk::GradientMagnitudeRecursiveGaussianImageFilter and then to the itk::SigmoidImageFilter. Finally, the output of the FastMarchingImageFilter is passed to a itk::BinaryThresholdImageFilter in order to produce a binary mask representing the segmented object.

The code in the following example illustrates the typical setup of a pipeline for performing segmentation with fast marching. First, the input image is smoothed using an edge-preserving filter. Then the magnitude of its gradient is computed and passed to a sigmoid filter. The result of the sigmoid filter is the image potential that will be used to affect the speed term of the differential equation.

Let's start by including the following headers. First we include the header of the CurvatureAnisotropicDiffusionImageFilter that will be used for removing noise from the input image.

```
#include "itkCurvatureAnisotropicDiffusionImageFilter.h"
```

The headers of the GradientMagnitudeRecursiveGaussianImageFilter and SigmoidImageFilter are included below. Together, these two filters will produce the image potential for regulating the speed term in the differential equation describing the evolution of the level set.

```
#include "itkGradientMagnitudeRecursiveGaussianImageFilter.h"
#include "itkSigmoidImageFilter.h"
```

Of course, we will need the otb::Image class and the FastMarchingImageFilter class. Hence we include their headers.

```
#include "otbImage.h"
#include "itkFastMarchingImageFilter.h"
```

The time-crossing map resulting from the FastMarchingImageFilter will be thresholded using the BinaryThresholdImageFilter. We include its header here.

```
#include "itkBinaryThresholdImageFilter.h"
```

Reading and writing images will be done with the otb::ImageFileReader and otb::ImageFileWriter.

```
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
```

We now define the image type using a pixel type and a particular dimension. In this case the float type is used for the pixels due to the requirements of the smoothing filter.

```
  typedef   float InternalPixelType;
  const unsigned int Dimension = 2;
  typedef otb::Image<InternalPixelType, Dimension> InternalImageType;
```

The output image, on the other hand, is declared to be binary.

```
typedef unsigned char                           OutputPixelType;
typedef otb::Image<OutputPixelType, Dimension> OutputImageType;
```

The type of the BinaryThresholdImageFilter filter is instantiated below using the internal image type and the output image type.

```
typedef itk::BinaryThresholdImageFilter<InternalImageType,
    OutputImageType>
ThresholdingFilterType;
ThresholdingFilterType::Pointer thresholder = ThresholdingFilterType::New();
```

The upper threshold passed to the BinaryThresholdImageFilter will define the time snapshot that we are taking from the time-crossing map.

```
thresholder->SetLowerThreshold(0.0);
thresholder->SetUpperThreshold(timeThreshold);

thresholder->SetOutsideValue(0);
thresholder->SetInsideValue(255);
```

We instantiate reader and writer types in the following lines.

```
typedef  otb::ImageFileReader<InternalImageType> ReaderType;
typedef  otb::ImageFileWriter<OutputImageType>   WriterType;
```

The CurvatureAnisotropicDiffusionImageFilter type is instantiated using the internal image type.

```
typedef   itk::CurvatureAnisotropicDiffusionImageFilter<
    InternalImageType,
    InternalImageType>  SmoothingFilterType;
```

Then, the filter is created by invoking the `New()` method and assigning the result to a `itk::SmartPointer`.

```
SmoothingFilterType::Pointer smoothing = SmoothingFilterType::New();
```

The types of the GradientMagnitudeRecursiveGaussianImageFilter and SigmoidImageFilter are instantiated using the internal image type.

```
typedef   itk::GradientMagnitudeRecursiveGaussianImageFilter<
    InternalImageType,
    InternalImageType>  GradientFilterType;

typedef   itk::SigmoidImageFilter<
    InternalImageType,
    InternalImageType>  SigmoidFilterType;
```

The corresponding filter objects are instantiated with the `New()` method.

```
GradientFilterType::Pointer gradientMagnitude = GradientFilterType::New();
SigmoidFilterType::Pointer  sigmoid = SigmoidFilterType::New();
```

The minimum and maximum values of the SigmoidImageFilter output are defined with the methods `SetOutputMinimum()` and `SetOutputMaximum()`. In our case, we want these two values to be 0.0 and 1.0 respectively in order to get a nice speed image to feed to the FastMarchingImageFilter.

```
sigmoid->SetOutputMinimum(0.0);
sigmoid->SetOutputMaximum(1.0);
```

We now declare the type of the FastMarchingImageFilter.

```
typedef  itk::FastMarchingImageFilter<InternalImageType,
    InternalImageType>
FastMarchingFilterType;
```

Then, we construct one filter of this class using the `New()` method.

```
FastMarchingFilterType::Pointer fastMarching = FastMarchingFilterType::New();
```

The filters are now connected in a pipeline shown in Figure 16.12 using the following lines.

```
smoothing->SetInput(reader->GetOutput());
gradientMagnitude->SetInput(smoothing->GetOutput());
sigmoid->SetInput(gradientMagnitude->GetOutput());
fastMarching->SetInput(sigmoid->GetOutput());
thresholder->SetInput(fastMarching->GetOutput());
writer->SetInput(thresholder->GetOutput());
```

The CurvatureAnisotropicDiffusionImageFilter class requires a couple of parameters to be defined. The following are typical values. However they may have to be adjusted depending on the amount of noise present in the input image.

```
smoothing->SetTimeStep(0.125);
smoothing->SetNumberOfIterations(10);
smoothing->SetConductanceParameter(2.0);
```

The GradientMagnitudeRecursiveGaussianImageFilter performs the equivalent of a convolution with a Gaussian kernel followed by a derivative operator. The sigma of this Gaussian can be used to control the range of influence of the image edges.

```
gradientMagnitude->SetSigma(sigma);
```

The SigmoidImageFilter class requires two parameters to define the linear transformation to be applied to the sigmoid argument. These parameters are passed using the `SetAlpha()` and `SetBeta()` methods. In the context of this example, the parameters are used to intensify the differences between regions of low and high values in the speed image. In an ideal case, the speed value should be 1.0 in the homogeneous regions and the value should decay rapidly to 0.0 around the edges of structures.

The heuristic for finding the values is the following. From the gradient magnitude image, let's call $K1$ the minimum value along the contour of the structure to be segmented. Then, let's call $K2$ an average value of the gradient magnitude in the middle of the structure. These two values indicate the dynamic range that we want to map to the interval $[0:1]$ in the speed image. We want the sigmoid to map $K1$ to 0.0 and $K2$ to 1.0. Given that $K1$ is expected to be higher than $K2$ and we want to map those values to 0.0 and 1.0 respectively, we want to select a negative value for alpha so that the sigmoid function will also do an inverse intensity mapping. This mapping will produce a speed image such that the level set will march rapidly on the homogeneous region and will definitely stop on the contour. The suggested value for beta is $(K1+K2)/2$ while the suggested value for alpha is $(K2-K1)/6$, which must be a negative number. In our simple example the values are provided by the user from the command line arguments. The user can estimate these values by observing the gradient magnitude image.

```
sigmoid->SetAlpha(alpha);
sigmoid->SetBeta(beta);
```

The FastMarchingImageFilter requires the user to provide a seed point from which the contour will expand. The user can actually pass not only one seed point but a set of them. A good set of seed points increases the chances of segmenting a complex object without missing parts. The use of multiple seeds also helps to reduce the amount of time needed by the front to visit a whole object and hence reduces the risk of leaks on the edges of regions visited earlier. For example, when segmenting an elongated object, it is undesirable to place a single seed at one extreme of the object since the front will need a long time to propagate to the other end of the object. Placing several seeds along the axis of the object will probably be the best strategy to ensure that the entire object is captured early in the expansion of the front. One of the important properties of level sets is their natural ability to fuse several fronts implicitly without any extra bookkeeping. The use of multiple seeds takes good advantage of this property.

The seeds are passed stored in a container. The type of this container is defined as `NodeContainer` among the FastMarchingImageFilter traits.

```
typedef FastMarchingFilterType::NodeContainer NodeContainer;
typedef FastMarchingFilterType::NodeType      NodeType;
NodeContainer::Pointer seeds = NodeContainer::New();
```

Nodes are created as stack variables and initialized with a value and an `itk::Index` position.

```
NodeType     node;
const double seedValue = 0.0;

node.SetValue(seedValue);
node.SetIndex(seedPosition);
```

The list of nodes is initialized and then every node is inserted using the `InsertElement()`.

```
seeds->Initialize();
seeds->InsertElement(0, node);
```

Structure	Seed Index	σ	α	β	Threshold	Output Image from left
Road	$(91,176)$	0.5	-0.5	3.0	100	First
Shadow	$(118,100)$	1.0	-0.5	3.0	100	Second
Building	$(145,21)$	0.5	-0.5	3.0	100	Third

Table 16.4: Parameters used for segmenting some structures shown in Figure 16.14 using the filter FastMarchingImageFilter. All of them used a stopping value of 100.

The set of seed nodes is now passed to the FastMarchingImageFilter with the method `SetTrialPoints()`.

```
fastMarching->SetTrialPoints(seeds);
```

The FastMarchingImageFilter requires the user to specify the size of the image to be produced as output. This is done using the `SetOutputSize()`. Note that the size is obtained here from the output image of the smoothing filter. The size of this image is valid only after the `Update()` methods of this filter has been called directly or indirectly.

```
fastMarching->SetOutputSize(
  reader->GetOutput()->GetBufferedRegion().GetSize());
```

Since the front representing the contour will propagate continuously over time, it is desirable to stop the process once a certain time has been reached. This allows us to save computation time under the assumption that the region of interest has already been computed. The value for stopping the process is defined with the method `SetStoppingValue()`. In principle, the stopping value should be a little bit higher than the threshold value.

```
fastMarching->SetStoppingValue(stoppingTime);
```

The invocation of the `Update()` method on the writer triggers the execution of the pipeline. As usual, the call is placed in a `try/catch` block should any errors occur or exceptions be thrown.

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& excep)
  {
  std::cerr << "Exception caught !" << std::endl;
  std::cerr << excep << std::endl;
  }
```

Now let's run this example using the input image `QB_Suburb.png` provided in the directory `Examples/Data`. We can easily segment structures by providing seeds in the appropriate locations. The following table presents the parameters used for some structures.

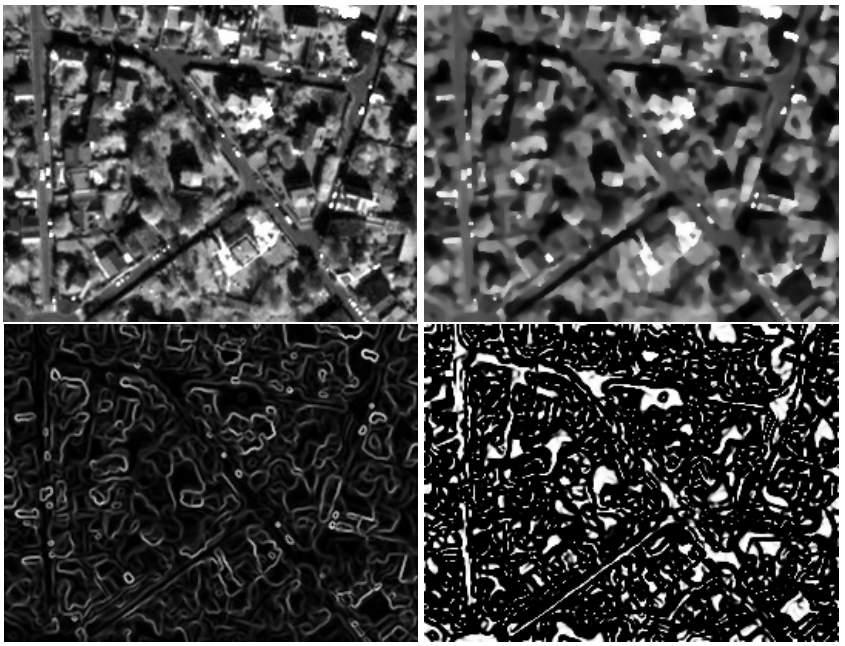


Figure 16.13: Images generated by the segmentation process based on the FastMarchingImageFilter. From left to right and top to bottom: input image to be segmented, image smoothed with an edge-preserving smoothing filter, gradient magnitude of the smoothed image, sigmoid of the gradient magnitude. This last image, the sigmoid, is used to compute the speed term for the front propagation

Figure 16.13 presents the intermediate outputs of the pipeline illustrated in Figure 16.12. They are from left to right: the output of the anisotropic diffusion filter, the gradient magnitude of the smoothed image and the sigmoid of the gradient magnitude which is finally used as the speed image for the FastMarchingImageFilter.

The following classes provide similar functionality:

- `itk::ShapeDetectionLevelSetImageFilter`
- `itk::GeodesicActiveContourLevelSetImageFilter`
- `itk::ThresholdSegmentationLevelSetImageFilter`
- `itk::CannySegmentationLevelSetImageFilter`
- `itk::LaplacianSegmentationLevelSetImageFilter`

See the ITK Software Guide for examples of the use of these classes.

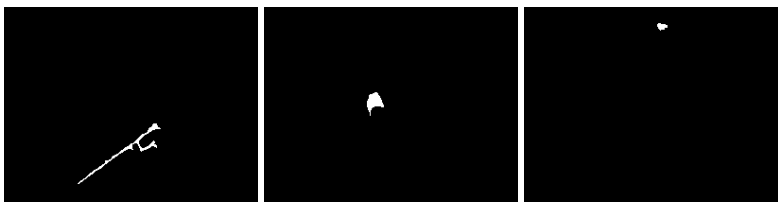


Figure 16.14: Images generated by the segmentation process based on the FastMarchingImageFilter. From left to right: segmentation of the road, shadow, building.

CHAPTER

SEVENTEEN

IMAGE SIMULATION

This chapter deals with image simulation algorithm. Using objects transmittance and reflectance and sensor characteristics, it can be possible to generate realistic hyperspectral synthetic set of data. This chapter includes PROSPECT (leaf optical properties) and SAIL (canopy bidirectional reflectance) model. Vegetation optical properties are modeled using PROSPECT model [71].

17.1 PROSAIL model

PROSAIL [71] model is the combinaison of PROSPECT leaf optical properties model and SAIL canopy bidirectional reflectance model. PROSAIL has also been used to develop new methods for retrieval of vegetation biophysical properties. It links the spectral variation of canopy reflectance, which is mainly related to leaf biochemical contents, with its directional variation, which is primarily related to canopy architecture and soil/vegetation contrast. This link is key to simultaneous estimation of canopy biophysical/structural variables for applications in agriculture, plant physiology, or ecology, at different scales. PROSAIL has become one of the most popular radiative transfer tools due to its ease of use, general robustness, and consistent validation by lab/field/space experiments over the years. Here we present a first example, which returns Hemispheric and Viewing reflectance for wavelength sampled from 400 to 2500*nm*. Inputs are leaf and Sensor (intrinsic and extrinsic) characteristics.

The source code for this example can be found in the file
`Examples/Simulation/ProsailModel.cxx`.

This example presents how to use PROSAIL (Prospect + Sail) model to generate viewing reflectance from leaf parameters, vegetation, and viewing parameters. Output can be used to simulate image for example.

Let's look at the minimal code required to use this algorithm. First, the following headers must be included.

```
#include "otbLeafParameters.h"
#include "otbSailModel.h"
```

```
#include "otbProspectModel.h"
```

We now define leaf parameters, which characterize vegetation composition.

```
  typedef otb::LeafParameters LeafParametersType;
```

Next the parameters variable is created by invoking the `New()` method and assigning the result to a `itk::SmartPointer`.

```
  LeafParametersType::Pointer leafParams = LeafParametersType::New();
```

Leaf characteristics is then set. Input parameters are :

- Chlorophyll concentration (Cab) in $\mu g/cm^2$.
- Carotenoid concentration (Car) in $\mu g/cm^2$.
- Brown pigment content (CBrown) in arbitrary unit.
- Water thickness EWT (Cw) in cm.
- Dry matter content LMA (Cm) in g/cm^2.
- Leaf structure parameter (N).

```
  double Cab = static_cast<double> (atof(argv[1]));
  double Car = static_cast<double> (atof(argv[2]));
  double CBrown = static_cast<double> (atof(argv[3]));
  double Cw = static_cast<double> (atof(argv[4]));
  double Cm = static_cast<double> (atof(argv[5]));
  double N = static_cast<double> (atof(argv[6]));

  leafParams->SetCab(Cab);
  leafParams->SetCar(Car);
  leafParams->SetCBrown(CBrown);
  leafParams->SetCw(Cw);
  leafParams->SetCm(Cm);
  leafParams->SetN(N);
```

Leaf parameters are used as prospect input

```
  typedef otb::ProspectModel ProspectType;
  ProspectType::Pointer prospect = ProspectType::New();

  prospect->SetInput(leafParams);
```

Now we use SAIL model to generate transmitance and reflectance spectrum. SAIL model is created by invoking the `New()` method and assigning the result to a `itk::SmartPointer`.

sail input parameters are :

- leaf area index (LAI).
- average leaf angle (Ang) in deg.
- soil coefficient (PSoil).
- diffuse/direct radiation (Skyl).
- hot spot (HSpot).
- solar zenith angle (TTS) in deg.
- observer zenith angle (TTO) in deg.
- azimuth (PSI) in deg.

```
double LAI = static_cast<double> (atof(argv[7]));
double Angl = static_cast<double> (atof(argv[8]));
double PSoil = static_cast<double> (atof(argv[9]));
double Skyl = static_cast<double> (atof(argv[10]));
double HSpot = static_cast<double> (atof(argv[11]));
double TTS = static_cast<double> (atof(argv[12]));
double TTO = static_cast<double> (atof(argv[13]));
double PSI = static_cast<double> (atof(argv[14]));

typedef otb::SailModel SailType;

SailType::Pointer sail = SailType::New();

sail->SetLAI(LAI);
sail->SetAngl(Angl);
sail->SetPSoil(PSoil);
sail->SetSkyl(Skyl);
sail->SetHSpot(HSpot);
sail->SetTTS(TTS);
sail->SetTTO(TTO);
sail->SetPSI(PSI);
```

Reflectance and Transmittance are set with prospect output.

```
sail->SetReflectance(prospect->GetReflectance());
sail->SetTransmittance(prospect->GetTransmittance());
```

The invocation of the `Update()` method triggers the execution of the pipeline.

```
sail->Update();
```

GetViewingReflectance method provides viewing reflectance vector (size $Nx2$, where N is the number of sampled wavelength values, columns corresponds respectively to wavelength and viewing reflectance) by calling *GetResponse*. *GetHemisphericalReflectance* method provides hemispherical reflectance vector (size $Nx2$, where N is the number ofsampled wavelength values, columns corresponds to wavelength and hemispherical reflectance) by calling *GetResponse*.

Note that PROSAIL simulation are done for 2100 samples starting from 400nm up to 2500nm

```
for (unsigned int i = 0; i < sail->GetViewingReflectance()->Size(); ++i)
  {
  std::cout << "wavelength  : ";
  std::cout << sail->GetViewingReflectance()->GetResponse()[i].first;
  std::cout << ". Viewing reflectance ";
  std::cout << sail->GetViewingReflectance()->GetResponse()[i].second;
  std::cout << ". Hemispherical reflectance ";
  std::cout << sail->GetHemisphericalReflectance()->GetResponse()[i].second;
  std::cout << std::endl;
  }
```

here you can found example parameters :

- Cab 30.0
- Car 10.0
- CBrown 0.0
- Cw 0.015
- Cm 0.009
- N 1.2
- LAI 2
- Angl 50
- PSoil 1
- Skyl 70
- HSpot 0.2
- TTS 30
- TTO 0
- PSI 0

More informations and data about leaf properties can be found at *Stéphane Jacquemoud* OPTICLEAF website.

17.2 Image Simulation

Here we present a complete pipeline to simulate image using sensor characteristics and objects reflectance and transmittance properties. This example use :

- input image
- label image : describes image object properties.
- label properties : describes each label characteristics.
- mask : vegetation image mask.
- cloud mask (optionnal).
- acquisition rarameter file : file containing the parameters for the acquisition.
- RSR File : File name for the relative spectral response to be used.
- sensor FTM file : File name for sensor spatial interpolation.

Algorithm is divided in following step :

1. LAI (Leaf Area Index) image estimation using NDVI formula.
2. Sensor Reduce Spectral Response (RSR) using PROSAIL reflectance output interpolated at sensor spectral bands.
3. Simulated image using Sensor RSR and Sensor FTM.

17.2.1 LAI image estimation

The source code for this example can be found in the file `Examples/Simulation/LAIFromNDVIImageTransform.cxx`.

This example presents a way to generate LAI (Leaf Area Index) image using formula dedicated to Formosat2. LAI Image is used as an input in Image Simulation process.

Let's look at the minimal code required to use this algorithm. First, the following headers must be included.

```
#include "otbMultiChannelRAndNIRIndexImageFilter.h"
#include "otbVegetationIndicesFunctor.h"
```

Filter type is a generic `otb::MultiChannelRAndNIRIndexImageFilter` using Formosat2 specific LAI `otb::LAIFromNDVIFormosat2Functor`.

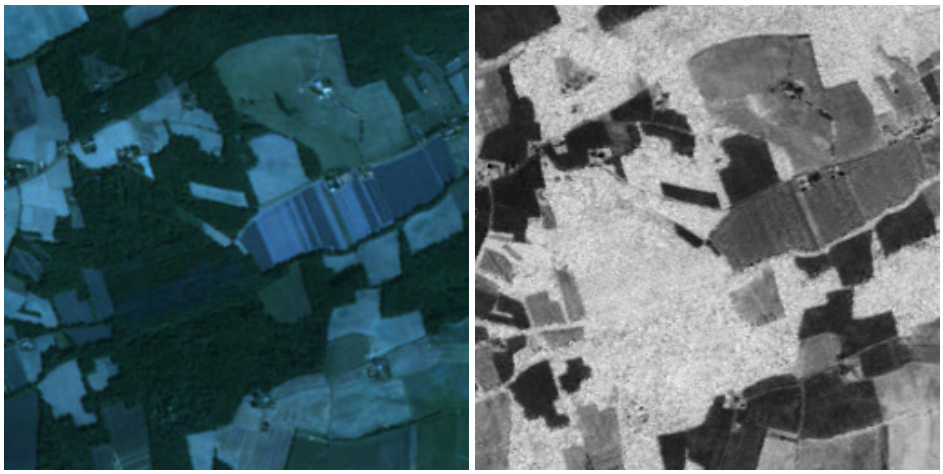


Figure 17.1: LAI generation *(right)* from NDVI applied on Formosat 2 Image *(left)* .

```
typedef otb::Functor::LAIFromNDVIFormosat2Functor
    <InputImageType::InternalPixelType,
    InputImageType::InternalPixelType, OutputImageType::PixelType> FunctorType;
typedef otb::MultiChannelRAndNIRIndexImageFilter
    <InputImageType, OutputImageType, FunctorType>
    MultiChannelRAndNIRIndexImageFilterType;
```

Next the filter is created by invoking the `New()` method and assigning the result to a `itk::SmartPointer`.

```
MultiChannelRAndNIRIndexImageFilterType::Pointer filter
= MultiChannelRAndNIRIndexImageFilterType::New();
```

filter input is set with input image

```
filter->SetInput(reader->GetOutput());
```

then red and nir channels index are set using `SetRedIndex()` and `SetNIRIndex()`

```
unsigned int redChannel = static_cast<unsigned int> (atoi(argv[5]));
unsigned int nirChannel = static_cast<unsigned int> (atoi(argv[6]));
filter->SetRedIndex(redChannel);
filter->SetNIRIndex(nirChannel);
```

The invocation of the `Update()` method triggers the execution of the pipeline.

```
filter->Update();
```

Figure 17.1 illustrates the LAI generation using Formosat 2 data.

17.2.2 Sensor RSR Image Simulation

The source code for this example can be found in the file
`Examples/Simulation/LAIAndPROSAILToSensorResponse.cxx`.

The following code is an example of Sensor spectral response image generated using image of labeled objects image, objects properties (vegetation classes are handled using PROSAIL model, non-vegetation classes are characterized using Aster database characteristics provided by a text file), acquisition parameters, sensor characteristics, and LAI (Leaf Area Index) image.

Sensor RSR is modeled by 6S (Second Simulation of a Satellite Signal in the Solar Spectrum) model [133]. Detailed information about 6S can be found here.

Let's look at the minimal code required to use this algorithm. First, the following headers must be included.

```
#include "otbProspectModel.h"
#include "otbSailModel.h"
#include "otbLeafParameters.h"
#include "otbSatelliteRSR.h"
#include "otbReduceSpectralResponse.h"
#include "otbImageSimulationMethod.h"
#include "otbSpatialisationFilter.h"
#include "otbAttributesMapLabelObject.h"
#include "otbSpectralResponse.h"
#include "itkTernaryFunctorImageFilter.h"
#include "otbVegetationIndicesFunctor.h"
#include "otbRAndNIRIndexImageFilter.h"
#include "otbVectorDataToLabelMapWithAttributesFilter.h"
```

`ImageUniqueValuesCalculator` class is defined here. Method `GetUniqueValues()` returns an array with all values contained in an image. This class is implemented and used to test if all labels in labeled image are present in label parameter file.

```
template < class TImage >
class ITK_EXPORT ImageUniqueValuesCalculator : public itk::Object
{
public:
  typedef ImageUniqueValuesCalculator<TImage>   Self;
  typedef itk::Object                           Superclass;
  typedef itk::SmartPointer<Self>               Pointer;
  typedef itk::SmartPointer<const Self>         ConstPointer;

  itkNewMacro(Self);

  itkTypeMacro(ImageUniqueValuesCalculator, itk::Object);

  itkStaticConstMacro(ImageDimension, unsigned int,
                      TImage::ImageDimension);

  typedef typename TImage::PixelType PixelType;

  typedef TImage ImageType;
```

```
  typedef std::vector<PixelType>           ArrayType;

  typedef typename ImageType::Pointer      ImagePointer;
  typedef typename ImageType::ConstPointer ImageConstPointer;

  virtual void SetImage( const ImageType * image )
    {
    if ( m_Image != image )
      {
      m_Image = image;
      this->Modified();
      }
    }


  ArrayType GetUniqueValues() const
  {
    typedef typename ImageType::IndexType IndexType;

    if( !m_Image )
      {
       itkExceptionMacro(<<"GetUniqueValues(): Null input image pointer.");
      }

    itk::ImageRegionConstIterator< ImageType > it( m_Image,
                                          m_Image->GetRequestedRegion() );

    ArrayType uniqueValues;

    uniqueValues.push_back(it.Get());
    ++it;
    while( !it.IsAtEnd() )
      {
      if( std::find(uniqueValues.begin(),
                    uniqueValues.end(), it.Get()) == uniqueValues.end())
        {
        uniqueValues.push_back(it.Get());
        }
      ++it;
      }

    return uniqueValues;
  }


protected:
  ImageUniqueValuesCalculator()
    {
    m_Image = NULL;
    }
  virtual ~ImageUniqueValuesCalculator()
  {
  }
  void PrintSelf(std::ostream& os, itk::Indent indent) const
```

```
  {
    Superclass::PrintSelf(os, indent);
    os << indent << "Image: " << m_Image.GetPointer() << std::endl;
  }

private:
  ImageUniqueValuesCalculator(const Self&); //purposely not implemented
  void operator=(const Self&); //purposely not implemented

  ImageConstPointer         m_Image;

};  // class ImageUniqueValuesCalculator
```

ProsailSimulatorFunctor functor is defined here.

```
template<class TLAI, class TLabel, class TMask, class TOutput,
  class TLabelSpectra, class TLabelParameter,
    class TAcquistionParameter, class TSatRSR>
class ProsailSimulatorFunctor
```

ProsailSimulatorFunctor functor is defined here.

```
  typedef TLAI LAIPixelType;
  typedef TLabel LabelPixelType;
  typedef TMask MaskPixelType;
  typedef TOutput OutputPixelType;
  typedef TLabelSpectra LabelSpectraType;
  typedef TLabelParameter LabelParameterType;
  typedef TAcquistionParameter AcquistionParameterType;
  typedef TSatRSR SatRSRType;
  typedef typename SatRSRType::Pointer SatRSRPointerType;
  typedef typename otb::ProspectModel ProspectType;
  typedef typename otb::SailModel SailType;

  typedef double PrecisionType;
  typedef std::pair<PrecisionType, PrecisionType> PairType;
  typedef typename std::vector<PairType> VectorPairType;
  typedef otb::SpectralResponse<PrecisionType, PrecisionType> ResponseType;
  typedef ResponseType::Pointer ResponsePointerType;
  typedef otb::ReduceSpectralResponse
      <ResponseType, SatRSRType> ReduceResponseType;
  typedef typename ReduceResponseType::Pointer
      ReduceResponseTypePointerType;
```

In this example spectra are generated form 400 to 2400nm. the number of simulated band is set by SimNbBands value.

```
  static const unsigned int SimNbBands = 2000;
```

mask value is read to know if the pixel have to be calculated, it is set to 0 otherwise.

```
    OutputPixelType pix;
    pix.SetSize(m_SatRSR->GetNbBands());
```

```
  if ((!mask && !m_InvertedMask) || (mask && m_InvertedMask))
    {
    for (unsigned int i = 0; i < m_SatRSR->GetNbBands(); i++)
      pix[i] = static_cast<typename OutputPixelType::ValueType> (0);
    return pix;
    }
```

Object reflectance `hxSpectrum` is calculated. If object label correspond to vegetation label then Prosail code is used, aster database is used otherwise.

```
  VectorPairType hxSpectrum;

  for (unsigned int i = 0; i < SimNbBands; i++)
    {
    PairType resp;
    resp.first = static_cast<PrecisionType> ((400.0 + i) / 1000);
    hxSpectrum.push_back(resp);
    }

  // either the spectrum has to be simulated by Prospect+Sail
  if (m_LabelParameters.find(label) != m_LabelParameters.end())
    {
    ProspectType::Pointer prospect = ProspectType::New();
    prospect->SetInput(m_LabelParameters[label]);

    SailType::Pointer sail = SailType::New();

    sail->SetLAI(lai);
    sail->SetAngl(m_AcquisitionParameters[std::string("Angl")]);
    sail->SetPSoil(m_AcquisitionParameters[std::string("PSoil")]);
    sail->SetSkyl(m_AcquisitionParameters[std::string("Skyl")]);
    sail->SetHSpot(m_AcquisitionParameters[std::string("HSpot")]);
    sail->SetTTS(m_AcquisitionParameters[std::string("TTS")]);
    sail->SetTTO(m_AcquisitionParameters[std::string("TTO")]);
    sail->SetPSI(m_AcquisitionParameters[std::string("PSI")]);
    sail->SetReflectance(prospect->GetReflectance());
    sail->SetTransmittance(prospect->GetTransmittance());
    sail->Update();

    for (unsigned int i = 0; i < SimNbBands; i++)
      {
      hxSpectrum[i].second = static_cast<typename OutputPixelType::ValueType>
        (sail->GetHemisphericalReflectance()->GetResponse()[i].second);
      }

    }
  // or the spectra has been set from outside the functor (ex. bare soil, etc.)
  else
    if (m_LabelSpectra.find(label) != m_LabelSpectra.end())
      {
      for (unsigned int i = 0; i < SimNbBands; i++)
        hxSpectrum[i].second =
            static_cast<typename OutputPixelType::ValueType>
              (m_LabelSpectra[label][i]);
```

```
      }
    // or the class does not exist
    else
      {
      for (unsigned int i = 0; i < SimNbBands; i++)
        hxSpectrum[i].second =
            static_cast<typename OutputPixelType::ValueType> (0);
      }
```

Spectral response `aResponse` is set using `hxSpectrum`.

```
    ResponseType::Pointer aResponse = ResponseType::New();
    aResponse->SetResponse(hxSpectrum);
```

Satellite RSR is initialized and set with `aResponse`.

```
    ReduceResponseTypePointerType reduceResponse = ReduceResponseType::New();
    reduceResponse->SetInputSatRSR(m_SatRSR);
    reduceResponse->SetInputSpectralResponse(aResponse);
    reduceResponse->CalculateResponse();
    VectorPairType reducedResponse =
        reduceResponse->GetReduceResponse()->GetResponse();
```

`pix` value is returned for desired Satellite bands

```
    for (unsigned int i = 0; i < m_SatRSR->GetNbBands(); i++)
      pix[i] =
          static_cast<typename OutputPixelType::ValueType>
            (reducedResponse[i].second);
    return pix;
```

`TernaryFunctorImageFilterWithNBands` class is defined here. This class inherits form `itk::TernaryFunctorImageFilter::`with additionnal nuber of band parameters. It's implementation is done to process Label, LAI, and mask image with Simulation functor.

```
template <class TInputImage1, class TInputImage2, class TInputImage3,
    class TOutputImage, class TFunctor>
class ITK_EXPORT TernaryFunctorImageFilterWithNBands :
  public itk::TernaryFunctorImageFilter< TInputImage1, TInputImage2,
  TInputImage3, TOutputImage, TFunctor >
{
public:
  typedef TernaryFunctorImageFilterWithNBands Self;
  typedef itk::TernaryFunctorImageFilter< TInputImage1, TInputImage2,
      TInputImage3, TOutputImage, TFunctor > Superclass;
  typedef itk::SmartPointer<Self>       Pointer;
  typedef itk::SmartPointer<const Self> ConstPointer;

  /** Method for creation through the object factory. */
  itkNewMacro(Self);

  /** Macro defining the type*/
  itkTypeMacro(TernaryFunctorImageFilterWithNBands, SuperClass);
```

```
  /** Accessors for the number of bands*/
  itkSetMacro(NumberOfOutputBands, unsigned int);
  itkGetConstMacro(NumberOfOutputBands, unsigned int);

protected:
  TernaryFunctorImageFilterWithNBands() {}
  virtual ~TernaryFunctorImageFilterWithNBands() {}

  void GenerateOutputInformation()
  {
    Superclass::GenerateOutputInformation();
    this->GetOutput()->SetNumberOfComponentsPerPixel( m_NumberOfOutputBands );
  }
private:
  TernaryFunctorImageFilterWithNBands(const Self &); //purposely not implemented
  void operator =(const Self&); //purposely not implemented

  unsigned int m_NumberOfOutputBands;


};
```

input images typedef are presented below. This example uses `double` LAI image, `binary` mask and cloud mask, and `integer` label image

```
  typedef double LAIPixelType;
  typedef unsigned short LabelType;
  typedef unsigned short MaskPixelType;
  typedef float OutputPixelType;
  // Image typedef
  typedef otb::Image<LAIPixelType, 2> LAIImageType;
  typedef otb::Image<LabelType, 2> LabelImageType;
  typedef otb::Image<MaskPixelType, 2> MaskImageType;
  typedef otb::VectorImage<OutputPixelType, 2> SimulatedImageType;
```

```
   Leaf parameters typedef is defined.
\small
\begin{lstlisting}
  typedef otb::LeafParameters LeafParametersType;
  typedef LeafParametersType::Pointer LeafParametersPointerType;
  typedef std::map<LabelType, LeafParametersPointerType> LabelParameterMapType;
```

Sensor spectral response typedef is defined

```
  typedef double PrecisionType;
  typedef std::vector<PrecisionType> SpectraType;
  typedef std::map<LabelType, SpectraType> SpectraParameterType;
```

Acquisition response typedef is defined

```
  typedef std::map<std::string, double> AcquistionParsType;
```

Satellite typedef is defined

```
typedef otb::SatelliteRSR<PrecisionType, PrecisionType> SatRSRType;
```

Filter type is the specific `TernaryFunctorImageFilterWithNBands` defined below with specific functor.

```
typedef otb::Functor::ProsailSimulatorFunctor
    <LAIPixelType, LabelType, MaskPixelType, SimulatedImageType::PixelType,
    SpectraParameterType, LabelParameterMapType, AcquistionParsType, SatRSRType>
      SimuFunctorType;
typedef otb::TernaryFunctorImageFilterWithNBands
    <LAIImageType, LabelImageType, MaskImageType, SimulatedImageType,
      SimuFunctorType> SimulatorType;
```

Acquisition parameters are loaded using text file. A detailled definition of acquisition parameters can be found in class `SailModel::`.

```
AcquistionParsType acquistionPars;
acquistionPars[std::string("Angl")] = 0.0;
acquistionPars[std::string("PSoil")] = 0.0;
acquistionPars[std::string("Skyl")] = 0.0;
acquistionPars[std::string("HSpot")] = 0.0;
acquistionPars[std::string("TTS")] = 0.0;
acquistionPars[std::string("TTO")] = 0.0;
acquistionPars[std::string("PSI")] = 0.0;

std::ifstream acquistionParsFile;

try
  {
  acquistionParsFile.open(apfname);
  }
catch (...)
  {
  std::cerr << "Could not open file " << apfname << std::endl;
  return EXIT_FAILURE;
  }

//unsigned int acPar = 0;
while (acquistionParsFile.good())
  {
  std::string line;
  std::getline(acquistionParsFile, line);
  std::stringstream ss(line);
  std::string parName;
  ss >> parName;
  double parValue;
  ss >> parValue;
  acquistionPars[parName] = parValue;

  }

acquistionParsFile.close();
```

Label parameters are loaded using text file. Two type of object characteristic can be found. If label corresponds to vegetation class, then leaf parameters are loaded. A detailled definition of leaf parameters can be found in class `otb::LeafParameters` class. Otherwise object reflectance is generated from 400 to 2400*nm* using Aster database.

```
LabelParameterMapType labelParameters;
std::ifstream labelParsFile;

SpectraParameterType spectraParameters;
try
  {
  labelParsFile.open(lpfname, std::ifstream::in);
  }
catch (...)
  {
  std::cerr << "Could not open file " << lpfname << std::endl;
  return EXIT_FAILURE;
  }

while (labelParsFile.good())
  {
  char fileLine[256];
  labelParsFile.getline(fileLine, 256);

  if (fileLine[0] != '#')
    {
    std::stringstream ss(fileLine);
    unsigned short label;
    ss >> label;
    unsigned short paramsOrSpectra;
    ss >> paramsOrSpectra;
    if (paramsOrSpectra == 1)
      {
      double Cab;
      ss >> Cab;
      double Car;
      ss >> Car;
      double CBrown;
      ss >> CBrown;
      double Cw;
      ss >> Cw;
      double Cm;
      ss >> Cm;
      double N;
      ss >> N;

      LeafParametersType::Pointer leafParams = LeafParametersType::New();

      leafParams->SetCab(Cab);
      leafParams->SetCar(Car);
      leafParams->SetCBrown(CBrown);
      leafParams->SetCw(Cw);
      leafParams->SetCm(Cm);
      leafParams->SetN(N);
```

```
      labelParameters[label] = leafParams;
      }
    else
      {
      std::string spectraFilename = rootPath;
      ss >> spectraFilename;
      spectraFilename = rootPath + spectraFilename;
      typedef otb::SpectralResponse<PrecisionType, PrecisionType> ResponseType;
      ResponseType::Pointer resp = ResponseType::New();

      // Coefficient 100 since Aster database is given in % reflectance
      resp->Load(spectraFilename, 100.0);

      SpectraType spec;
      for (unsigned int i = 0; i < SimuFunctorType::SimNbBands; i++)
        //Prosail starts at 400 and lambda in Aster DB is in micrometers
        spec.push_back
          (static_cast<PrecisionType> ((*resp)((i + 400.0) / 1000.0)));

      spectraParameters[label] = spec;
      }
    }
  }

labelParsFile.close();
```

LAI image is read.

```
LAIReaderType::Pointer laiReader = LAIReaderType::New();
laiReader->SetFileName(laiifname);
laiReader->Update();
LAIImageType::Pointer laiImage = laiReader->GetOutput();
```

Label image is then read. Label image is processed using `ImageUniqueValuesCalculator` in order to check if all the labels are present in the labelParameters file.

```
LabelReaderType::Pointer labelReader = LabelReaderType::New();
labelReader->SetFileName(lifname);
labelReader->Update();

LabelImageType::Pointer labelImage = labelReader->GetOutput();

typedef otb::ImageUniqueValuesCalculator<LabelImageType> UniqueCalculatorType;

UniqueCalculatorType::Pointer uniqueCalculator = UniqueCalculatorType::New();

uniqueCalculator->SetImage(labelImage);

UniqueCalculatorType::ArrayType uniqueVals =
    uniqueCalculator->GetUniqueValues();
std::cout << "Labels are " << std::endl;
UniqueCalculatorType::ArrayType::const_iterator uvIt = uniqueVals.begin();

while (uvIt != uniqueVals.end())
```

```
  {
  std::cout << (*uvIt) << ", ";
  ++uvIt;
  }

std::cout << std::endl;

uvIt = uniqueVals.begin();

while (uvIt != uniqueVals.end())
  {
  if (labelParameters.find(static_cast<LabelType>
      (*uvIt)) == labelParameters.end() &&
      spectraParameters.find(static_cast<LabelType> (*uvIt)) ==
          spectraParameters.end() &&
      static_cast<LabelType> (*uvIt) != 0)
    {
    std::cout << "label " << (*uvIt) << " not found in " <<
        lpfname << std::endl;
    return EXIT_FAILURE;
    }
  ++uvIt;
  }
```

Mask image is read. If cloud mask is filename is given, a new mask image is generated with masks concatenation.

```
MaskReaderType::Pointer miReader = MaskReaderType::New();
miReader->SetFileName(mifname);
miReader->UpdateOutputInformation();
MaskImageType::Pointer maskImage = miReader->GetOutput();

if (cmifname != NULL)
  {

  MaskReaderType::Pointer cmiReader = MaskReaderType::New();
  cmiReader->SetFileName(cmifname);
  cmiReader->UpdateOutputInformation();

  typedef itk::OrImageFilter
      <MaskImageType, MaskImageType, MaskImageType> OrType;
  OrType::Pointer orfilter = OrType::New();

  orfilter->SetInput1(miReader->GetOutput());
  orfilter->SetInput2(cmiReader->GetOutput());

  orfilter->Update();
  maskImage = orfilter->GetOutput();

  }
```

A test is done. All images must have the same size.

```
if (laiImage->GetLargestPossibleRegion().GetSize()[0] !=
```

```
    labelImage->GetLargestPossibleRegion().GetSize()[0] ||
    laiImage->GetLargestPossibleRegion().GetSize()[1] !=
        labelImage->GetLargestPossibleRegion().GetSize()[1] ||
    laiImage->GetLargestPossibleRegion().GetSize()[0] !=
        maskImage->GetLargestPossibleRegion().GetSize()[0] ||
    laiImage->GetLargestPossibleRegion().GetSize()[1] !=
        maskImage->GetLargestPossibleRegion().GetSize()[1])
  {
  std::cerr << "Image of labels, mask and LAI image must have the same size"
      << std::endl;
  return EXIT_FAILURE;
  }
```

Satellite RSR (Reduced Spectral Response) is defined using filename and band number given by command line arguments.

```
SatRSRType::Pointer satRSR = SatRSRType::New();
satRSR->SetNbBands(nbBands);
satRSR->SetSortBands(false);
satRSR->Load(rsfname);

for (unsigned int i = 0; i < nbBands; ++i)
  std::cout << i << " " << (satRSR->GetRSR())[i]->GetInterval().first << " "
      << (satRSR->GetRSR())[i]->GetInterval().second << std::endl;
```

At this step all initialization have been done. The next step is to implement and initialize simulation functor `ProsailSimulatorFunctor`.

```
SimuFunctorType simuFunctor;
simuFunctor.SetLabelParameters(labelParameters);
simuFunctor.SetLabelSpectra(spectraParameters);
simuFunctor.SetAcquisitionParameters(acquistionPars);
simuFunctor.SetRSR(satRSR);
simuFunctor.SetInvertedMask(true);
```

Inputs and Functor are plugged to simulator filter.

```
SimulatorType::Pointer simulator = SimulatorType::New();
simulator->SetInput1(laiImage);
simulator->SetInput2(labelImage);
simulator->SetInput3(maskImage);
simulator->SetFunctor(simuFunctor);
simulator->SetNumberOfOutputBands(nbBands);
```

The invocation of the `Update()` method triggers the execution of the pipeline.

```
simulator->Update();
```

CHAPTER

EIGHTEEN

DIMENSION REDUCTION

Dimension reduction is a statistical process, which concentrates the amount of information in multivariate data into a fewer number of variables (or dimensions). An interesting review of the domain has been done by Fodor [47].

Though there are plenty of non-linear methods in the litterature, OTB provides only linear dimension reduction techniques applied to images for now.

Usually, linear dimension-reduction algorithms try to find a set of linear combinations of the input image bands that maximise a given criterion, often chosen so that image information concentrates on the first components. Algorithms differs by the criterion to optimise and also by their handling of the signal or image noise.

In remote-sensing images processing, dimension reduction algorithms are of great interest for denoising, or as a preliminary processing for classification of feature images or unmixing of hyperspectral images. In addition to the denoising effect, the advantage of dimension reduction in the two latter is that it lowers the size of the data to be analysed, and as such, speeds up the processing time without too much loss of accuracy.

18.1 Principal Component Analysis

The source code for this example can be found in the file
`Examples/DimensionReduction/PCAExample.cxx`.

This example illustrates the use of the `otb::PCAImageFilter`. This filter computes a Principal Component Analysis using an efficient method based on the inner product in order to compute the covariance matrix.

The first step required to use this filter is to include its header file.

```
#include "otbPCAImageFilter.h"
```

We start by defining the types for the images and the reader and the writer. We choose to work with a `otb::VectorImage`, since we will produce a multi-channel image (the principal components) from a multi-channel input image.

```
typedef otb::VectorImage<PixelType, Dimension> ImageType;
typedef otb::ImageFileReader<ImageType>        ReaderType;
typedef otb::ImageFileWriter<ImageType>        WriterType;
```

We instantiate now the image reader and we set the image file name.

```
ReaderType::Pointer reader     = ReaderType::New();
reader->SetFileName(inputFileName);
```

We define the type for the filter. It is templated over the input and the output image types and also the transformation direction. The internal structure of this filter is a filter-to-filter like structure. We can now the instantiate the filter.

```
typedef otb::PCAImageFilter<ImageType, ImageType,
                            otb::Transform::FORWARD> PCAFilterType;
PCAFilterType::Pointer pcafilter     = PCAFilterType::New();
```

The only parameter needed for the PCA is the number of principal components required as output. Principal components are linear combination of input components (here the input image bands), which are selected using Singular Value Decomposition eigen vectors sorted by eigen value. We can choose to get less Principal Components than the number of input bands.

```
pcafilter->SetNumberOfPrincipalComponentsRequired(
  numberOfPrincipalComponentsRequired);
```

We now instantiate the writer and set the file name for the output image.

```
WriterType::Pointer writer     = WriterType::New();
writer->SetFileName(outputFilename);
```

We finally plug the pipeline and trigger the PCA computation with the method `Update()` of the writer.

```
pcafilter->SetInput(reader->GetOutput());
writer->SetInput(pcafilter->GetOutput());

writer->Update();
```

`otb::PCAImageFilter` allows also to compute inverse transformation from PCA coefficients. In reverse mode, the covariance matrix or the transformation matrix (which may not be square) has to be given.

```
typedef otb::PCAImageFilter< ImageType, ImageType,
                             otb::Transform::INVERSE > InvPCAFilterType;
InvPCAFilterType::Pointer invFilter = InvPCAFilterType::New();
```

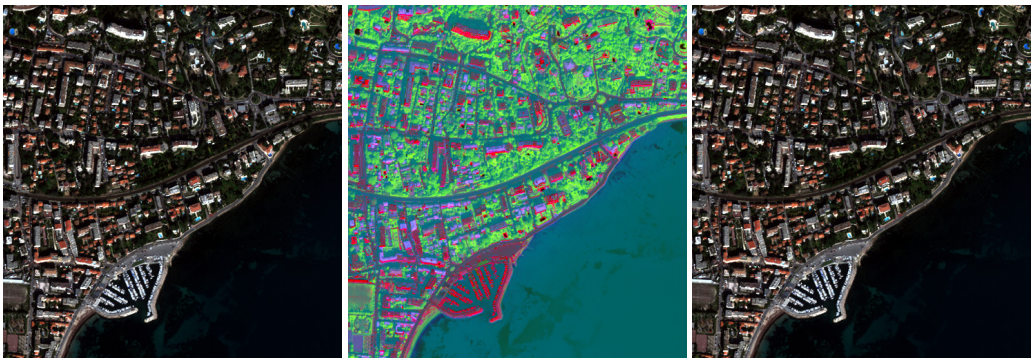


Figure 18.1: Result of applying the `otb::PCAImageFilter` to an image. From left to right: original image, color composition with first three principal components and output of the inverse mode (the input RGB image).

```
invFilter->SetInput(pcafilter->GetOutput());
invFilter->SetTransformationMatrix(pcafilter->GetTransformationMatrix());

WriterType::Pointer invWriter = WriterType::New();
invWriter->SetFileName(outputInverseFilename );
invWriter->SetInput(invFilter->GetOutput() );

invWriter->Update();
```

Figure 18.1 shows the result of applying forward and reverse PCA transformation to a 8 bands Worldview2 image.

18.2 Noise-Adjusted Principal Components Analysis

The source code for this example can be found in the file `Examples/DimensionReduction/NAPCAExample.cxx`.

This example illustrates the use of the `otb::NAPCAImageFilter`. This filter computes a Noise-Adjusted Principal Component Analysis transform [85] using an efficient method based on the inner product in order to compute the covariance matrix.

The Noise-Adjusted Principal Component Analysis transform is a sequence of two Principal Component Analysis transforms. The first transform is based on an estimated covariance matrix of the noise, and intends to whiten the input image (noise with unit variance and no correlation between bands).

The second Principal Component Analysis is then applied to the noise-whitened image, giving the Maximum Noise Fraction transform. Applying PCA on noise-whitened image consists in ranking

Principal Components according to signal to noise ratio.

It is basically a reformulation of the Maximum Noise Fraction algorithm.

The first step required to use this filter is to include its header file.

```
#include "otbNAPCAImageFilter.h"
```

We also need to include the header of the noise filter.

```
#include "otbLocalActivityVectorImageFilter.h"
```

We start by defining the types for the images, the reader and the writer. We choose to work with a `otb::VectorImage`, since we will produce a multi-channel image (the principal components) from a multi-channel input image.

```
  typedef otb::VectorImage<PixelType, Dimension> ImageType;
  typedef otb::ImageFileReader<ImageType>        ReaderType;
  typedef otb::ImageFileWriter<ImageType>        WriterType;
```

We instantiate now the image reader and we set the image file name.

```
  ReaderType::Pointer reader     = ReaderType::New();
  reader->SetFileName(inputFileName);
```

In contrast with standard Principal Component Analysis, NA-PCA needs an estimation of the noise correlation matrix in the dataset prior to transformation.

A classical approach is to use spatial gradient images and infer the noise correlation matrix from it. The method of noise estimation can be customized by templating the `otb::NAPCAImageFilter` with the desired noise estimation method.

In this implementation, noise is estimated from a local window. We define the type of the noise filter.

```
  typedef otb::LocalActivityVectorImageFilter<ImageType,ImageType> NoiseFilterType;
```

We define the type for the filter. It is templated over the input and the output image types, the noise estimation filter type, and also the transformation direction. The internal structure of this filter is a filter-to-filter like structure. We can now the instantiate the filter.

```
  typedef otb::NAPCAImageFilter<ImageType, ImageType,
                                NoiseFilterType,
                                otb::Transform::FORWARD> NAPCAFilterType;
  NAPCAFilterType::Pointer napcafilter     = NAPCAFilterType::New();
```

We then set the number of principal components required as output. We can choose to get less PCs than the number of input bands.

```
  napcafilter->SetNumberOfPrincipalComponentsRequired(
    numberOfPrincipalComponentsRequired);
```

We set the radius of the sliding window for noise estimation.

```
NoiseFilterType::RadiusType radius = {{ vradius, vradius }};
napcafilter->GetNoiseImageFilter()->SetRadius(radius);
```

Last, we can activate normalisation.

```
napcafilter->SetUseNormalization( normalization );
```

We now instantiate the writer and set the file name for the output image.

```
WriterType::Pointer writer     = WriterType::New();
writer->SetFileName(outputFilename);
```

We finally plug the pipeline and trigger the NA-PCA computation with the method `Update()` of the writer.

```
napcafilter->SetInput(reader->GetOutput());
writer->SetInput(napcafilter->GetOutput());

writer->Update();
```

`otb::NAPCAImageFilter` allows also to compute inverse transformation from NA-PCA coefficients. In reverse mode, the covariance matrix or the transformation matrix (which may not be square) has to be given.

```
typedef otb::NAPCAImageFilter< ImageType, ImageType,
                               NoiseFilterType,
                               otb::Transform::INVERSE > InvNAPCAFilterType;
InvNAPCAFilterType::Pointer invFilter = InvNAPCAFilterType::New();

invFilter->SetMeanValues( napcafilter->GetMeanValues() );
if ( normalization )
  invFilter->SetStdDevValues( napcafilter->GetStdDevValues() );
invFilter->SetTransformationMatrix( napcafilter->GetTransformationMatrix() );
invFilter->SetInput(napcafilter->GetOutput());

WriterType::Pointer invWriter = WriterType::New();
invWriter->SetFileName(outputInverseFilename );
invWriter->SetInput(invFilter->GetOutput() );

invWriter->Update();
```

Figure 18.2 shows the result of applying forward and reverse NA-PCA transformation to a 8 bands Worldview2 image.

18.3 Maximum Noise Fraction

The source code for this example can be found in the file `Examples/DimensionReduction/MNFExample.cxx`.

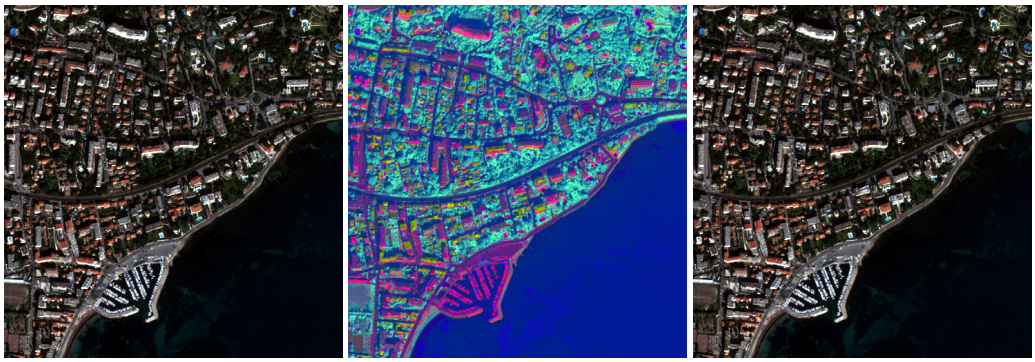


Figure 18.2: Result of applying the `otb::NAPCAImageFilter` to an image. From left to right: original image, color composition with first three principal components and output of the inverse mode (the input RGB image).

This example illustrates the use of the `otb::MNFImageFilter`. This filter computes a Maximum Noise Fraction transform [52] using an efficient method based on the inner product in order to compute the covariance matrix.

The Maximum Noise Fraction transform is a sequence of two Principal Component Analysis transforms. The first transform is based on an estimated covariance matrix of the noise, and intends to whiten the input image (noise with unit variance and no correlation between bands).

The second Principal Component Analysis is then applied to the noise-whitened image, giving the Maximum Noise Fraction transform.

In this implementation, noise is estimated from a local window.

The first step required to use this filter is to include its header file.

```
#include "otbMNFImageFilter.h"
```

We also need to include the header of the noise filter.

```
#include "otbLocalActivityVectorImageFilter.h"
```

We start by defining the types for the images, the reader, and the writer. We choose to work with a `otb::VectorImage`, since we will produce a multi-channel image (the principal components) from a multi-channel input image.

```
  typedef otb::VectorImage<PixelType, Dimension> ImageType;
  typedef otb::ImageFileReader<ImageType>        ReaderType;
  typedef otb::ImageFileWriter<ImageType>        WriterType;
```

We instantiate now the image reader and we set the image file name.

```
  ReaderType::Pointer reader     = ReaderType::New();
  reader->SetFileName(inputFileName);
```

In contrast with standard Principal Component Analysis, MNF needs an estimation of the noise correlation matrix in the dataset prior to transformation.

A classical approach is to use spatial gradient images and infer the noise correlation matrix from it. The method of noise estimation can be customized by templating the `otb::MNFImageFilter` with the desired noise estimation method.

In this implementation, noise is estimated from a local window. We define the type of the noise filter.

```
typedef otb::LocalActivityVectorImageFilter<ImageType,ImageType> NoiseFilterType;
```

We define the type for the filter. It is templated over the input and the output image types and also the transformation direction. The internal structure of this filter is a filter-to-filter like structure. We can now the instantiate the filter.

```
typedef otb::MNFImageFilter<ImageType, ImageType,
                            NoiseFilterType,
                            otb::Transform::FORWARD> MNFFilterType;
MNFFilterType::Pointer MNFfilter     = MNFFilterType::New();
```

We then set the number of principal components required as output. We can choose to get less PCs than the number of input bands.

```
MNFfilter->SetNumberOfPrincipalComponentsRequired(
  numberOfPrincipalComponentsRequired);
```

We set the radius of the sliding window for noise estimation.

```
NoiseFilterType::RadiusType radius = {{ vradius, vradius }};
MNFfilter->GetNoiseImageFilter()->SetRadius(radius);
```

Last, we can activate normalisation.

```
MNFfilter->SetUseNormalization( normalization );
```

We now instantiate the writer and set the file name for the output image.

```
WriterType::Pointer writer     = WriterType::New();
writer->SetFileName(outputFilename);
```

We finally plug the pipeline and trigger the MNF computation with the method `Update()` of the writer.

```
MNFfilter->SetInput(reader->GetOutput());
writer->SetInput(MNFfilter->GetOutput());

writer->Update();
```

Figure 18.3: Result of applying the `otb::MNFImageFilter` to an image. From left to right: original image, color composition with first three principal components and output of the inverse mode (the input RGB image).

`otb::MNFImageFilter` allows also to compute inverse transformation from MNF coefficients. In reverse mode, the covariance matrix or the transformation matrix (which may not be square) has to be given.

```
typedef otb::MNFImageFilter< ImageType, ImageType,
                             NoiseFilterType,
                             otb::Transform::INVERSE > InvMNFFilterType;
InvMNFFilterType::Pointer invFilter = InvMNFFilterType::New();

invFilter->SetMeanValues( MNFfilter->GetMeanValues() );
if ( normalization )
  invFilter->SetStdDevValues( MNFfilter->GetStdDevValues() );
invFilter->SetTransformationMatrix( MNFfilter->GetTransformationMatrix() );
invFilter->SetInput(MNFfilter->GetOutput());

WriterType::Pointer invWriter = WriterType::New();
invWriter->SetFileName(outputInverseFilename );
invWriter->SetInput(invFilter->GetOutput() );

invWriter->Update();
```

Figure 18.3 shows the result of applying forward and reverse MNF transformation to a 8 bands Worldview2 image.

18.4 Fast Independant Component Analysis

The source code for this example can be found in the file `Examples/DimensionReduction/ICAExample.cxx`.

This example illustrates the use of the `otb::FastICAImageFilter`. This filter computes a Fast

Independent Components Analysis transform.

Like Principal Components Analysis, Independent Component Analysis [76] computes a set of orthogonal linear combinations, but the criterion of Fast ICA is different: instead of maximizing variance, it tries to maximize statistical independence between components.

In the Fast ICA algorithm [66], statistical independence is measured by evaluating non-Gaussianity of the components, and the maximization is done in an iterative way.

The first step required to use this filter is to include its header file.

```
#include "otbFastICAImageFilter.h"
```

We start by defining the types for the images, the reader, and the writer. We choose to work with a `otb::VectorImage`, since we will produce a multi-channel image (the independent components) from a multi-channel input image.

```
typedef otb::VectorImage<PixelType, Dimension> ImageType;
typedef otb::ImageFileReader<ImageType>        ReaderType;
typedef otb::ImageFileWriter<ImageType>        WriterType;
```

We instantiate now the image reader and we set the image file name.

```
ReaderType::Pointer reader     = ReaderType::New();
reader->SetFileName(inputFileName);
```

We define the type for the filter. It is templated over the input and the output image types and also the transformation direction. The internal structure of this filter is a filter-to-filter like structure. We can now the instantiate the filter.

```
typedef otb::FastICAImageFilter<ImageType, ImageType,
                                otb::Transform::FORWARD> FastICAFilterType;
FastICAFilterType::Pointer FastICAfilter     = FastICAFilterType::New();
```

We then set the number of independent components required as output. We can choose to get less ICs than the number of input bands.

```
FastICAfilter->SetNumberOfPrincipalComponentsRequired(
  numberOfPrincipalComponentsRequired);
```

We set the number of iterations of the ICA algorithm.

```
FastICAfilter->SetNumberOfIterations(numIterations);
```

We also set the μ parameter.

```
FastICAfilter->SetMu( mu );
```

We now instantiate the writer and set the file name for the output image.

```
WriterType::Pointer writer     = WriterType::New();
writer->SetFileName(outputFilename);
```

We finally plug the pipeline and trigger the ICA computation with the method `Update()` of the writer.

```
FastICAfilter->SetInput(reader->GetOutput());
writer->SetInput(FastICAfilter->GetOutput());

writer->Update();
```

`otb::FastICAImageFilter` allows also to compute inverse transformation from ICA coefficients. In reverse mode, the covariance matrix or the transformation matrix (which may not be square) has to be given.

```
typedef otb::FastICAImageFilter< ImageType, ImageType,
                                 otb::Transform::INVERSE > InvFastICAFilterType;
InvFastICAFilterType::Pointer invFilter = InvFastICAFilterType::New();

invFilter->SetMeanValues( FastICAfilter->GetMeanValues() );
invFilter->SetStdDevValues( FastICAfilter->GetStdDevValues() );
invFilter->SetTransformationMatrix( FastICAfilter->GetTransformationMatrix() );
invFilter->SetPCATransformationMatrix(
                          FastICAfilter->GetPCATransformationMatrix() );
invFilter->SetInput(FastICAfilter->GetOutput());

WriterType::Pointer invWriter = WriterType::New();
invWriter->SetFileName(outputInverseFilename );
invWriter->SetInput(invFilter->GetOutput() );

invWriter->Update();
```

Figure 18.4 shows the result of applying forward and reverse FastICA transformation to a 8 bands Worldview2 image.

18.5 Maximum Autocorrelation Factor

The source code for this example can be found in the file
`Examples/DimensionReduction/MaximumAutocorrelationFactor.cxx`.

This example illustrates the class `otb::MaximumAutocorrelationFactorImageFilter`, which performs a Maximum Autocorrelation Factor transform [100]. Like PCA, MAF tries to find a set of orthogonal linear transform, but the criterion to maximize is the spatial auto-correlation rather than the variance.

Auto-correlation is the correlation between the component and a unitary shifted version of the component.

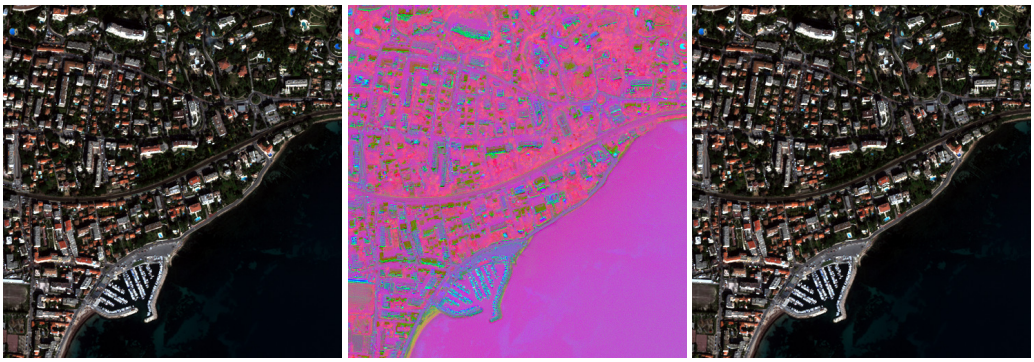


Figure 18.4: Result of applying the `otb::FastICAImageFilter` to an image. From left to right: original image, color composition with first three principal components and output of the inverse mode (the input RGB image).

Please note that the inverse transform is not implemented yet.

We start by including the corresponding header file.

```
#include "otbMaximumAutocorrelationFactorImageFilter.h"
```

We then define the types for the input image and the output image.

```
typedef otb::VectorImage<unsigned short, 2> InputImageType;
typedef otb::VectorImage<double, 2>         OutputImageType;
```

We can now declare the types for the reader. Since the images can be very large, we will force the pipeline to use streaming. For this purpose, the file writer will be streamed. This is achieved by using the `otb::ImageFileWriter` class.

```
typedef otb::ImageFileReader<InputImageType>    ReaderType;
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

The `otb::MultivariateAlterationDetectorImageFilter` is templated over the type of the input images and the type of the generated change image.

```
typedef otb::MaximumAutocorrelationFactorImageFilter<InputImageType,
                                                     OutputImageType> FilterType;
```

The different elements of the pipeline can now be instantiated.

```
ReaderType::Pointer reader = ReaderType::New();
WriterType::Pointer writer = WriterType::New();
FilterType::Pointer filter = FilterType::New();
```

We set the parameters of the different elements of the pipeline.

Figure 18.5: Results of the Maximum Autocorrelation Factor algorithm applied to a 8 bands Worldview2 image (3 first components).

```
reader->SetFileName(infname);
writer->SetFileName(outfname);
```

We build the pipeline by plugging all the elements together.

```
filter->SetInput(reader->GetOutput());
writer->SetInput(filter->GetOutput());
```

And then we can trigger the pipeline update, as usual.

```
writer->Update();
```

Figure 18.5 shows the results of Maximum Autocorrelation Factor applied to an 8 bands Worldview2 image.

CHAPTER

NINETEEN

CLASSIFICATION

19.1 Introduction

Image classification consists in extracting added-value information from images. Such processing methods classify pixels within images into geographical connected zones with similar properties, and identified by a common class label. The classification can be either unsupervised or supervised.

Unsupervised classification does not require any additional information about the properties of the input image to classify it. On the contrary, supervised methods need a preliminary learning to be computed over training datasets having similar properties than the image to classify, in order to build a classification model.

19.2 Unsupervised classification

19.2.1 K-Means Classification

Simple version

The source code for this example can be found in the file
`Examples/Classification/ScalarImageKmeansClassifier.cxx`.

This example shows how to use the KMeans model for classifying the pixel of a scalar image.

The `itk::Statistics::ScalarImageKmeansImageFilter` is used for taking a scalar image and applying the K-Means algorithm in order to define classes that represents statistical distributions of intensity values in the pixels. The classes are then used in this filter for generating a labeled image where every pixel is assigned to one of the classes.

```
#include "otbImage.h"
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
```

```
#include "itkScalarImageKmeansImageFilter.h"
```

First we define the pixel type and dimension of the image that we intend to classify. With this image type we can also declare the `otb::ImageFileReader` needed for reading the input image, create one and set its input filename.

```
typedef signed short PixelType;
const unsigned int Dimension = 2;

typedef otb::Image<PixelType, Dimension> ImageType;

typedef otb::ImageFileReader<ImageType> ReaderType;
ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(inputImageFileName);
```

With the `ImageType` we instantiate the type of the `itk::ScalarImageKmeansImageFilter` that will compute the K-Means model and then classify the image pixels.

```
typedef itk::ScalarImageKmeansImageFilter<ImageType> KMeansFilterType;

KMeansFilterType::Pointer kmeansFilter = KMeansFilterType::New();

kmeansFilter->SetInput(reader->GetOutput());

const unsigned int numberOfInitialClasses = atoi(argv[4]);
```

In general the classification will produce as output an image whose pixel values are integers associated to the labels of the classes. Since typically these integers will be generated in order (0, 1, 2, ...N), the output image will tend to look very dark when displayed with naive viewers. It is therefore convenient to have the option of spreading the label values over the dynamic range of the output image pixel type. When this is done, the dynamic range of the pixels is divided by the number of classes in order to define the increment between labels. For example, an output image of 8 bits will have a dynamic range of [0:255], and when it is used for holding four classes, the non-contiguous labels will be (0, 64, 128, 192). The selection of the mode to use is done with the method `SetUseContiguousLabels()`.

```
const unsigned int useNonContiguousLabels = atoi(argv[3]);

kmeansFilter->SetUseNonContiguousLabels(useNonContiguousLabels);
```

For each one of the classes we must provide a tentative initial value for the mean of the class. Given that this is a scalar image, each one of the means is simply a scalar value. Note however that in a general case of K-Means, the input image would be a vector image and therefore the means will be vectors of the same dimension as the image pixels.

```
for (unsigned k = 0; k < numberOfInitialClasses; ++k)
  {
  const double userProvidedInitialMean = atof(argv[k + argoffset]);
  kmeansFilter->AddClassWithInitialMean(userProvidedInitialMean);
  }
```

The itk::ScalarImageKmeansImageFilter is predefined for producing an 8 bits scalar image as output. This output image contains labels associated to each one of the classes in the K-Means algorithm. In the following lines we use the OutputImageType in order to instantiate the type of a otb::ImageFileWriter. Then create one, and connect it to the output of the classification filter.

```
typedef KMeansFilterType::OutputImageType OutputImageType;

typedef otb::ImageFileWriter<OutputImageType> WriterType;

WriterType::Pointer writer = WriterType::New();

writer->SetInput(kmeansFilter->GetOutput());

writer->SetFileName(outputImageFileName);
```

We are now ready for triggering the execution of the pipeline. This is done by simply invoking the Update() method in the writer. This call will propagate the update request to the reader and then to the classifier.

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& excp)
  {
  std::cerr << "Problem encountered while writing ";
  std::cerr << " image file : " << argv[2] << std::endl;
  std::cerr << excp << std::endl;
  return EXIT_FAILURE;
  }
```

At this point the classification is done, the labeled image is saved in a file, and we can take a look at the means that were found as a result of the model estimation performed inside the classifier filter.

```
KMeansFilterType::ParametersType estimatedMeans =
  kmeansFilter->GetFinalMeans();

const unsigned int numberOfClasses = estimatedMeans.Size();

for (unsigned int i = 0; i < numberOfClasses; ++i)
  {
  std::cout << "cluster[" << i << "] ";
  std::cout << "    estimated mean : " << estimatedMeans[i] << std::endl;
  }
```

Figure 19.1 illustrates the effect of this filter with three classes. The means can be estimated by ScalarImageKmeansModelEstimator.cxx.

The source code for this example can be found in the file
Examples/Classification/ScalarImageKmeansModelEstimator.cxx.

This example shows how to compute the KMeans model of an Scalar Image.

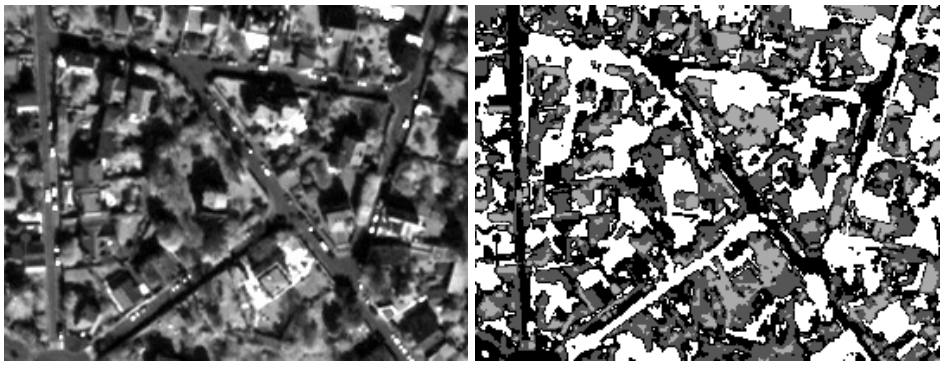


Figure 19.1: Effect of the KMeans classifier. Left: original image. Right: image of classes.

The `itk::Statistics::KdTreeBasedKmeansEstimator` is used for taking a scalar image and applying the K-Means algorithm in order to define classes that represents statistical distributions of intensity values in the pixels. One of the drawbacks of this technique is that the spatial distribution of the pixels is not considered at all. It is common therefore to combine the classification resulting from K-Means with other segmentation techniques that will use the classification as a prior and add spatial information to it in order to produce a better segmentation.

```
// Create a List from the scalar image
typedef itk::Statistics::ImageToListSampleAdaptor<ImageType> AdaptorType;

AdaptorType::Pointer adaptor = AdaptorType::New();

adaptor->SetImage(reader->GetOutput());

// Define the Measurement vector type from the AdaptorType
typedef AdaptorType::MeasurementVectorType MeasurementVectorType;

// Create the K-d tree structure
typedef itk::Statistics::WeightedCentroidKdTreeGenerator<
    AdaptorType>
TreeGeneratorType;

TreeGeneratorType::Pointer treeGenerator = TreeGeneratorType::New();

treeGenerator->SetSample(adaptor);
treeGenerator->SetBucketSize(16);
treeGenerator->Update();

typedef TreeGeneratorType::KdTreeType                          TreeType;
typedef itk::Statistics::KdTreeBasedKmeansEstimator<TreeType> EstimatorType;

EstimatorType::Pointer estimator = EstimatorType::New();

const unsigned int numberOfClasses = 4;
```

```
EstimatorType::ParametersType initialMeans(numberOfClasses);
initialMeans[0] = 25.0;
initialMeans[1] = 125.0;
initialMeans[2] = 250.0;

estimator->SetParameters(initialMeans);

estimator->SetKdTree(treeGenerator->GetOutput());
estimator->SetMaximumIteration(200);
estimator->SetCentroidPositionChangesThreshold(0.0);
estimator->StartOptimization();

EstimatorType::ParametersType estimatedMeans = estimator->GetParameters();

for (unsigned int i = 0; i < numberOfClasses; ++i)
  {
  std::cout << "cluster[" << i << "] " << std::endl;
  std::cout << "    estimated mean : " << estimatedMeans[i] << std::endl;
  }
```

General approach

The source code for this example can be found in the file
`Examples/Classification/KMeansImageClassificationExample.cxx`.

The K-Means classification proposed by ITK for images is limited to scalar images and is not streamed. In this example, we show how the use of the `otb::KMeansImageClassificationFilter` allows for a simple implementation of a K-Means classification application. We will start by including the appropirate header file.

```
#include "otbKMeansImageClassificationFilter.h"
```

We will assume double precision input images and will also define the type for the labeled pixels.

```
const unsigned int Dimension = 2;
typedef double          PixelType;
typedef unsigned short LabeledPixelType;
```

Our classifier will be genric enough to be able to process images with any number of bands. We read the images as `otb::VectorImages`. The labeled image will be a scalar image.

```
typedef otb::VectorImage<PixelType, Dimension>  ImageType;
typedef otb::Image<LabeledPixelType, Dimension> LabeledImageType;
```

We can now define the type for the classifier filter, which is templated over its input and output image types.

```
typedef otb::KMeansImageClassificationFilter<ImageType, LabeledImageType>
ClassificationFilterType;
typedef ClassificationFilterType::KMeansParametersType KMeansParametersType;
```

And finally, we define the reader and the writer. Since the images to classify can be very big, we will use a streamed writer which will trigger the streaming ability of the classifier.

```
typedef otb::ImageFileReader<ImageType>                ReaderType;
typedef otb::ImageFileWriter<LabeledImageType> WriterType;
```

We instantiate the classifier and the reader objects and we set their parameters. Please note the call of the `GenerateOutputInformation()` method on the reader in order to have available the information about the input image (size, number of bands, etc.) without needing to actually read the image.

```
ClassificationFilterType::Pointer filter = ClassificationFilterType::New();

ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(infname);
reader->GenerateOutputInformation();
```

The classifier needs as input the centroids of the classes. We declare the parameter vector, and we read the centroids from the arguments of the program.

```
const unsigned int sampleSize =
  ClassificationFilterType::MaxSampleDimension;
const unsigned int   parameterSize = nbClasses * sampleSize;
KMeansParametersType parameters;

parameters.SetSize(parameterSize);
parameters.Fill(0);

for (unsigned int i = 0; i < nbClasses; ++i)
  {
  for (unsigned int j = 0; j <
       reader->GetOutput()->GetNumberOfComponentsPerPixel(); ++j)
    {
    parameters[i * sampleSize + j] =
      atof(argv[4 + i *
                reader->GetOutput()->GetNumberOfComponentsPerPixel()
                + j]);
    }
  }

std::cout << "Parameters: " << parameters << std::endl;
```

We set the parameters for the classifier, we plug the pipeline and trigger its execution by updating the output of the writer.

```
filter->SetCentroids(parameters);
filter->SetInput(reader->GetOutput());

WriterType::Pointer writer = WriterType::New();
writer->SetInput(filter->GetOutput());
writer->SetFileName(outfname);
writer->Update();
```

k-d Tree Based k-Means Clustering

The source code for this example can be found in the file
`Examples/Classification/KdTreeBasedKMeansClustering.cxx`.

K-means clustering is a popular clustering algorithm because it is simple and usually converges to a reasonable solution. The k-means algorithm works as follows:

1. Obtains the initial k means input from the user.
2. Assigns each measurement vector in a sample container to its closest mean among the k number of means (i.e., update the membership of each measurement vectors to the nearest of the k clusters).
3. Calculates each cluster's mean from the newly assigned measurement vectors (updates the centroid (mean) of k clusters).
4. Repeats step 2 and step 3 until it meets the termination criteria.

The most common termination criteria is that if there is no measurement vector that changes its cluster membership from the previous iteration, then the algorithm stops.

The `itk::Statistics::KdTreeBasedKmeansEstimator` is a variation of this logic. The k-means clustering algorithm is computationally very expensive because it has to recalculate the mean at each iteration. To update the mean values, we have to calculate the distance between k means and each and every measurement vector. To reduce the computational burden, the KdTreeBasedKmeansEstimator uses a special data structure: the k-d tree (`itk::Statistics::KdTree`) with additional information. The additional information includes the number and the vector sum of measurement vectors under each node under the tree architecture.

With such additional information and the k-d tree data structure, we can reduce the computational cost of the distance calculation and means. Instead of calculating each measurement vectors and k means, we can simply compare each node of the k-d tree and the k means. This idea of utilizing a k-d tree can be found in multiple articles [5] [104] [77]. Our implementation of this scheme follows the article by the Kanungo et al [77].

We use the `itk::Statistics::ListSample` as the input sample, the `itk::Vector` as the measurement vector. The following code snippet includes their header files.

```
#include "itkVector.h"
#include "itkListSample.h"
```

Since this k-means algorithm requires a `itk::Statistics::KdTree` object as an input, we include the KdTree class header file. As mentioned above, we need a k-d tree with the vector sum and the number of measurement vectors. Therefore we use the `itk::Statistics::WeightedCentroidKdTreeGenerator` instead of the `itk::Statistics::KdTreeGenerator` that generate a k-d tree without such additional information.

```
#include "itkKdTree.h"
#include "itkWeightedCentroidKdTreeGenerator.h"
```

The KdTreeBasedKmeansEstimator class is the implementation of the k-means algorithm. It does not create k clusters. Instead, it returns the mean estimates for the k clusters.

```
#include "itkKdTreeBasedKmeansEstimator.h"
```

To generate the clusters, we must create k instances of `itk::Statistics::EuclideanDistanceMetric` function as the membership functions for each cluster and plug that—along with a sample—into an `itk::Statistics::SampleClassifierFilter` object to get a `itk::Statistics::MembershipSample` that stores pairs of measurement vectors and their associated class labels (k labels).

```
#include "itkMinimumDecisionRule.h"
#include "itkEuclideanDistanceMetric.h"
#include "itkSampleClassifierFilter.h"
```

We will fill the sample with random variables from two normal distribution using the `itk::Statistics::NormalVariateGenerator`.

```
#include "itkNormalVariateGenerator.h"
```

Since the `NormalVariateGenerator` class only supports 1-D, we define our measurement vector type as one component vector. We then, create a `ListSample` object for data inputs. Each measurement vector is of length 1. We set this using the `SetMeasurementVectorSize()` method.

```
typedef itk::Vector<double,
    1>
MeasurementVectorType;
typedef itk::Statistics::ListSample<MeasurementVectorType> SampleType;
SampleType::Pointer sample = SampleType::New();
sample->SetMeasurementVectorSize(1);
```

The following code snippet creates a NormalVariateGenerator object. Since the random variable generator returns values according to the standard normal distribution (The mean is zero, and the standard deviation is one), before pushing random values into the `sample`, we change the mean and standard deviation. We want two normal (Gaussian) distribution data. We have two for loops. Each `for` loop uses different mean and standard deviation. Before we fill the `sample` with the second distribution data, we call `Initialize(random seed)` method, to recreate the pool of random variables in the `normalGenerator`.

To see the probability density plots from the two distribution, refer to the Figure 19.2.

```
typedef itk::Statistics::NormalVariateGenerator NormalGeneratorType;
NormalGeneratorType::Pointer normalGenerator = NormalGeneratorType::New();
```

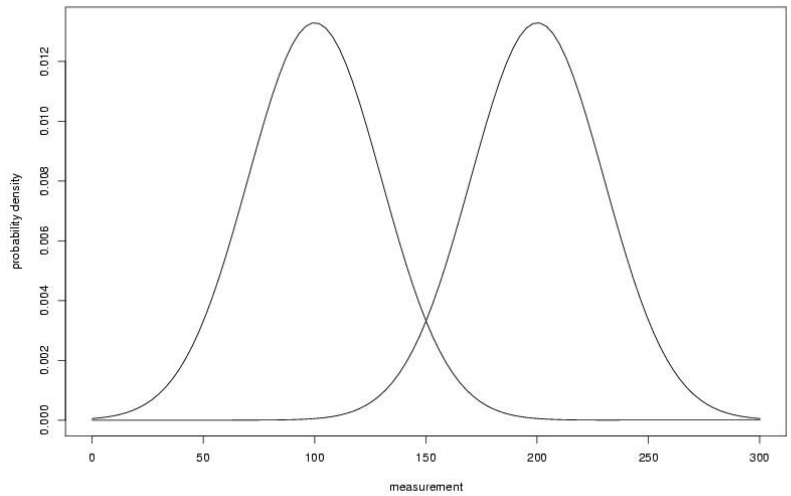


Figure 19.2: Two normal distributions' probability density plot (The means are 100 and 200, and the standard deviation is 30)

```
normalGenerator->Initialize(101);

MeasurementVectorType mv;
double                mean = 100;
double                standardDeviation = 30;
for (unsigned int i = 0; i < 100; ++i)
  {
  mv[0] = (normalGenerator->GetVariate() * standardDeviation) + mean;
  sample->PushBack(mv);
  }

normalGenerator->Initialize(3024);
mean = 200;
standardDeviation = 30;
for (unsigned int i = 0; i < 100; ++i)
  {
  mv[0] = (normalGenerator->GetVariate() * standardDeviation) + mean;
  sample->PushBack(mv);
  }
```

We create a k-d tree.

```
typedef itk::Statistics::WeightedCentroidKdTreeGenerator<SampleType>
TreeGeneratorType;
TreeGeneratorType::Pointer treeGenerator = TreeGeneratorType::New();
```

```
treeGenerator->SetSample(sample);
treeGenerator->SetBucketSize(16);
treeGenerator->Update();
```

Once we have the k-d tree, it is a simple procedure to produce k mean estimates.

We create the KdTreeBasedKmeansEstimator. Then, we provide the initial mean values using the `SetParameters()`. Since we are dealing with two normal distribution in a 1-D space, the size of the mean value array is two. The first element is the first mean value, and the second is the second mean value. If we used two normal distributions in a 2-D space, the size of array would be four, and the first two elements would be the two components of the first normal distribution's mean vector. We plug-in the k-d tree using the `SetKdTree()`.

The remaining two methods specify the termination condition. The estimation process stops when the number of iterations reaches the maximum iteration value set by the `SetMaximumIteration()`, or the distances between the newly calculated mean (centroid) values and previous ones are within the threshold set by the `SetCentroidPositionChangesThreshold()`. The final step is to call the `StartOptimization()` method.

The for loop will print out the mean estimates from the estimation process.

```
typedef TreeGeneratorType::KdTreeType                          TreeType;
typedef itk::Statistics::KdTreeBasedKmeansEstimator<TreeType> EstimatorType;
EstimatorType::Pointer estimator = EstimatorType::New();

EstimatorType::ParametersType initialMeans(2);
initialMeans[0] = 0.0;
initialMeans[1] = 0.0;

estimator->SetParameters(initialMeans);
estimator->SetKdTree(treeGenerator->GetOutput());
estimator->SetMaximumIteration(200);
estimator->SetCentroidPositionChangesThreshold(0.0);
estimator->StartOptimization();

EstimatorType::ParametersType estimatedMeans = estimator->GetParameters();

for (unsigned int i = 0; i < 2; ++i)
  {
  std::cout << "cluster[" << i << "] " << std::endl;
  std::cout << "    estimated mean : " << estimatedMeans[i] << std::endl;
  }
```

If we are only interested in finding the mean estimates, we might stop. However, to illustrate how a classifier can be formed using the statistical classification framework. We go a little bit further in this example.

Since the k-means algorithm is an minimum distance classifier using the estimated k means and the measurement vectors. We use the EuclideanDistanceMetric class as membership functions. Our choice for the decision rule is the `itk::Statistics::MinimumDecisionRule` that returns the

index of the membership functions that have the smallest value for a measurement vector.

After creating a SampleClassifierFilter object and a MinimumDecisionRule object, we plug-in the `decisionRule` and the `sample` to the classifier. Then, we must specify the number of classes that will be considered using the `SetNumberOfClasses()` method.

The remainder of the following code snippet shows how to use user-specified class labels. The classification result will be stored in a MembershipSample object, and for each measurement vector, its class label will be one of the two class labels, 100 and 200 (`unsigned int`).

```
  typedef itk::Statistics::DistanceToCentroidMembershipFunction<
    MeasurementVectorType >   MembershipFunctionType;
  typedef itk::Statistics::EuclideanDistanceMetric< MeasurementVectorType >
DistanceMetricType;

  typedef itk::Statistics::MinimumDecisionRule DecisionRuleType;
  DecisionRuleType::Pointer decisionRule = DecisionRuleType::New();

  typedef itk::Statistics::SampleClassifierFilter<SampleType> ClassifierType;
  ClassifierType::Pointer classifier = ClassifierType::New();

  classifier->SetDecisionRule(decisionRule);
  classifier->SetInput(sample);
  classifier->SetNumberOfClasses(2);


  typedef ClassifierType::ClassLabelVectorObjectType
ClassLabelVectorObjectType;
  ClassLabelVectorObjectType::Pointer classLabels  = ClassLabelVectorObjectType::New();
  classLabels->Get().push_back(100);
  classLabels->Get().push_back(200);

  classifier->SetClassLabels(classLabels);
```

The `classifier` is almost ready to do the classification process except that it needs two membership functions that represents two clusters respectively.

In this example, the two clusters are modeled by two Euclidean distance functions. The distance function (model) has only one parameter, its mean (centroid) set by the `SetOrigin()` method. To plug-in two distance functions, we call the `AddMembershipFunction()` method. Then invocation of the `Update()` method will perform the classification.

```
  typedef ClassifierType::MembershipFunctionVectorObjectType
MembershipFunctionVectorObjectType;
  MembershipFunctionVectorObjectType::Pointer membershipFunctions =
                                      MembershipFunctionVectorObjectType::New();

//  std::vector<MembershipFunctionType::Pointer> membershipFunctions;

  DistanceMetricType::OriginType origin(
    sample->GetMeasurementVectorSize());
  int index = 0;
  for (unsigned int i = 0; i < 2; ++i)
```

```
    {
    MembershipFunctionType::Pointer membershipFunction1 = MembershipFunctionType::New();
    for (unsigned int j = 0; j < sample->GetMeasurementVectorSize(); ++j)
      {
      origin[j] = estimatedMeans[index++];
      }
      DistanceMetricType::Pointer distanceMetric = DistanceMetricType::New();
      distanceMetric->SetOrigin(origin);
      membershipFunction1->SetDistanceMetric( distanceMetric );
//    classifier->AddMembershipFunction(membershipFunctions[i].GetPointer());
      membershipFunctions->Get().push_back(membershipFunction1.GetPointer() );
    }

  classifier->SetMembershipFunctions(membershipFunctions);
  classifier->Update();
```

The following code snippet prints out the measurement vectors and their class labels in the `sample`.

```
  const ClassifierType::MembershipSampleType* membershipSample =
    classifier->GetOutput();
  ClassifierType::MembershipSampleType::ConstIterator iter = membershipSample->Begin();

  while (iter != membershipSample->End())
    {
    std::cout << "measurement vector = " << iter.GetMeasurementVector()
              << "class label = " << iter.GetClassLabel()
              << std::endl;
    ++iter;
    }
```

19.2.2 Kohonen's Self Organizing Map

The Self Organizing Map, SOM, introduced by Kohonen is a non-supervised neural learning algorithm. The map is composed of neighboring cells which are in competition by means of mutual interactions and they adapt in order to match characteristic patterns of the examples given during the learning. The SOM is usually on a plane (2D).

The algorithm implements a nonlinear projection from a high dimensional feature space to a lower dimension space, usually 2D. It is able to find the correspondence between a set of structured data and a network of much lower dimension while keeping the topological relationships existing in the feature space. Thanks to this topological organization, the final map presents clusters and their relationships.

Kohonen's SOM is usually represented as an array of cells where each cell is, i, associated to a feature (or weight) vector $\underline{m_i} = [m_{i1}, m_{i2}, \cdots, m_{in}]^T \in \mathbb{R}^n$ (figure 19.3).

A cell (or neuron) in the map is a good detector for a given input vector $\underline{x} = [x_1, x_2, \cdots, x_n]^T \in \mathbb{R}^n$ if the latter is *close* to the former. This distance between vectors can be represented by the scalar

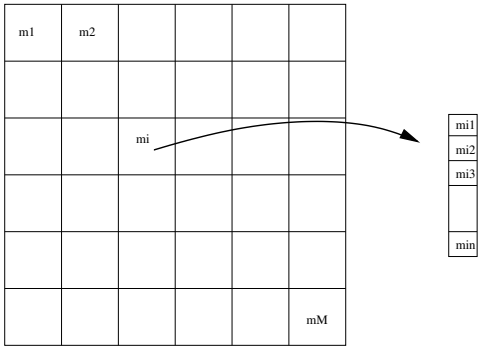


Figure 19.3: Kohonen's Self Organizing Map

product $\underline{x}^T \cdot \underline{m_i}$, but for most of the cases other distances can be used, as for instance the Euclidean one. The cell having the weight vector closest to the input vector is called the *winner*.

The goal of the learning step is to get a map which is representative of an input example set. It is an iterative procedure which consists in passing each input example to the map, testing the response of each neuron and modifying the map to get it closer to the examples.

Algorithm 1 *SOM learning:*

1. $t = 0$.
2. *Initialize the weight vectors of the map (randomly, for instance).*
3. *While $t <$ number of iterations, do:*
   (a) $k = 0$.
   (b) *While $k <$ number of examples, do:*
      i. *Find the vector $\underline{m}_i(t)$ which minimizes the distance $d(\underline{x}_k, \underline{m}_i(t))$*
      ii. *For a neighborhood $N_c(t)$ around the winner cell, apply the transformation:*

$$\underline{m}_i(t+1) = \underline{m}_i(t) + \beta(t)\,[\underline{x}_k(t) - \underline{m}_i(t)] \tag{19.1}$$

      iii. $k = k + 1$
   (c) $t = t + 1$.

In 19.1, $\beta(t)$ is a decreasing function with the geometrical distance to the winner cell. For instance:

$$\beta(t) = \beta_0(t) e^{-\frac{\|r_i - r_c\|^2}{\sigma^2(t)}}, \tag{19.2}$$

with $\beta_0(t)$ and $\sigma(t)$ decreasing functions with time and $\underline{r}$ the cell coordinates in the output – map – space.

Therefore the algorithm consists in getting the map closer to the learning set. The use of a neighborhood around the winner cell allows the organization of the map into areas which specialize in the recognition of different patterns. This neighborhood also ensures that cells which are topologically close are also close in terms of the distance defined in the feature space.

Building a color table

The source code for this example can be found in the file `Examples/Learning/SOMExample.cxx`.

This example illustrates the use of the `otb::SOM` class for building Kohonen's Self Organizing Maps.

We will use the SOM in order to build a color table from an input image. Our input image is coded with 3×8 bits and we would like to code it with only 16 levels. We will use the SOM in order to learn which are the 16 most representative RGB values of the input image and we will assume that this is the optimal color table for the image.

The first thing to do is include the header file for the class. We will also need the header files for the map itself and the activation map builder whose utility will be explained at the end of the example.

```
#include "otbSOMMap.h"
#include "otbSOM.h"
#include "otbSOMActivationBuilder.h"
```

Since the `otb::SOM` class uses a distance, we will need to include the header file for the one we want to use

```
#include "itkEuclideanDistanceMetric.h"
```

The Self Organizing Map itself is actually an N-dimensional image where each pixel contains a neuron. In our case, we decide to build a 2-dimensional SOM, where the neurons store RGB values with floating point precision.

```
  const unsigned int Dimension = 2;
  typedef double                                  PixelType;
  typedef otb::VectorImage<PixelType, Dimension> ImageType;
  typedef ImageType::PixelType                    VectorType;
```

The distance that we want to apply between the RGB values is the Euclidean one. Of course we could choose to use other type of distance, as for instance, a distance defined in any other color space.

```
  typedef itk::Statistics::EuclideanDistanceMetric<VectorType> DistanceType;
```

We can now define the type for the map. The `otb::SOMMap::c`lass is templated over the neuron type – `PixelType` here –, the distance type and the number of dimensions. Note that the number of dimensions of the map could be different from the one of the images to be processed.

```
typedef otb::SOMMap<VectorType, DistanceType, Dimension> MapType;
```

We are going to perform the learning directly on the pixels of the input image. Therefore, the image type is defined using the same pixel type as we used for the map. We also define the type for the imge file reader.

```
typedef otb::ImageFileReader<ImageType> ReaderType;
```

Since the `otb::SOM` class works on lists of samples, it will need to access the input image through an adaptor. Its type is defined as follows:

```
typedef itk::Statistics::ListSample<VectorType> SampleListType;
```

We can now define the type for the SOM, which is templated over the input sample list and the type of the map to be produced and the two functors that hold the training behavior.

```
typedef otb::Functor::CzihoSOMLearningBehaviorFunctor
LearningBehaviorFunctorType;
typedef otb::Functor::CzihoSOMNeighborhoodBehaviorFunctor
NeighborhoodBehaviorFunctorType;
typedef otb::SOM<SampleListType, MapType,
    LearningBehaviorFunctorType, NeighborhoodBehaviorFunctorType>
SOMType;
```

As an alternative to standart `SOMType`, one can decide to use an `otb::PeriodicSOM`, which behaves like `otb::SOM` but is to be considered to as a torus instead of a simple map. Hence, the neighborhood behavior of the winning neuron does not depend on its location on the map... `otb::PeriodicSOM` is defined in otbPeriodicSOM.h.

We can now start building the pipeline. The first step is to instantiate the reader and pass its output to the adaptor.

```
ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(inputFileName);
reader->Update();

SampleListType::Pointer sampleList = SampleListType::New();
sampleList->SetMeasurementVectorSize(reader->GetOutput()->GetVectorLength());

itk::ImageRegionIterator<ImageType> imgIter (reader->GetOutput(),
                                             reader->GetOutput()->
                                             GetBufferedRegion());
imgIter.GoToBegin();

itk::ImageRegionIterator<ImageType> imgIterEnd (reader->GetOutput(),
                                                reader->GetOutput()->
                                                GetBufferedRegion());
```

```
imgIterEnd.GoToEnd();

do
  {
  sampleList->PushBack(imgIter.Get());
  ++imgIter;
  }
while (imgIter != imgIterEnd);
```

We can now instantiate the SOM algorithm and set the sample list as input.

```
SOMType::Pointer som = SOMType::New();
som->SetListSample(sampleList);
```

We use a `SOMType::SizeType` array in order to set the sizes of the map.

```
SOMType::SizeType size;
size[0] = sizeX;
size[1] = sizeY;
som->SetMapSize(size);
```

The initial size of the neighborhood of each neuron is set in the same way.

```
SOMType::SizeType radius;
radius[0] = neighInitX;
radius[1] = neighInitY;
som->SetNeighborhoodSizeInit(radius);
```

The other parameters are the number of iterations, the initial and the final values for the learning rate – β – and the maximum initial value for the neurons (the map will be randomly initialized).

```
som->SetNumberOfIterations(nbIterations);
som->SetBetaInit(betaInit);
som->SetBetaEnd(betaEnd);
som->SetMaxWeight(static_cast<PixelType>(initValue));
```

Now comes the intialization of the functors.

```
LearningBehaviorFunctorType learningFunctor;
learningFunctor.SetIterationThreshold(radius, nbIterations);
som->SetBetaFunctor(learningFunctor);

NeighborhoodBehaviorFunctorType neighborFunctor;
som->SetNeighborhoodSizeFunctor(neighborFunctor);
som->Update();
```

Finally, we set up the las part of the pipeline where the plug the output of the SOM into the writer. The learning procedure is triggered by calling the `Update()` method on the writer. Since the map is itself an image, we can write it to disk with an `otb::ImageFileWriter`.

Figure 19.4 shows the result of the SOM learning. Since we have performed a learning on RGB pixel values, the produced SOM can be interpreted as an optimal color table for the input image. It

Figure 19.4: Result of the SOM learning. Left: RGB image. Center: SOM. Right: Activation map

can be observed that the obtained colors are topologically organised, so similar colors are also close in the map. This topological organisation can be exploited to further reduce the number of coding levels of the pixels without performing a new learning: we can subsample the map to get a new color table. Also, a bilinear interpolation between the neurons can be used to increase the number of coding levels.

We can now compute the activation map for the input image. The activation map tells us how many times a given neuron is activated for the set of examples given to the map. The activation map is stored as a scalar image and an integer pixel type is usually enough.

```
typedef unsigned char OutputPixelType;

typedef otb::Image<OutputPixelType, Dimension> OutputImageType;
typedef otb::ImageFileWriter<OutputImageType>  ActivationWriterType;
```

In a similar way to the `otb::SOM` class the `otb::SOMActivationBuilder` is templated over the sample list given as input, the SOM map type and the activation map to be built as output.

```
typedef otb::SOMActivationBuilder<SampleListType, MapType,
    OutputImageType> SOMActivationBuilderType;
```

We instantiate the activation map builder and set as input the SOM map build before and the image (using the adaptor).

```
SOMActivationBuilderType::Pointer somAct
  = SOMActivationBuilderType::New();
somAct->SetInput(som->GetOutput());
somAct->SetListSample(sampleList);
somAct->Update();
```

The final step is to write the activation map to a file.

```
if (actMapFileName != NULL)
  {
  ActivationWriterType::Pointer actWriter = ActivationWriterType::New();
```

```
    actWriter->SetFileName(actMapFileName);
```

The righthand side of figure 19.4 shows the activation map obtained.

SOM Classification

The source code for this example can be found in the file
`Examples/Learning/SOMClassifierExample.cxx`.

This example illustrates the use of the `otb::SOMClassifier` class for performing a classification using an existing Kohonen's Self Organizing. Actually, the SOM classification consists only in the attribution of the winner neuron index to a given feature vector.

We will use the SOM created in section 19.2.2 and we will assume that each neuron represents a class in the image.

The first thing to do is include the header file for the class.

```
#include "otbSOMClassifier.h"
```

As for the SOM learning step, we must define the types for the `otb::SOMMap`, and therefore, also for the distance to be used. We will also define the type for the SOM reader, which is actually an `otb::ImageFileReader::w`hich the appropiate image type.

```
  typedef itk::Statistics::EuclideanDistanceMetric<PixelType>   DistanceType;
  typedef otb::SOMMap<PixelType, DistanceType, Dimension> SOMMapType;
  typedef otb::ImageFileReader<SOMMapType>                SOMReaderType;
```

The classification will be performed by the `otb::SOMClassifier::`, which, as most of the classifiers, works on `itk::Statistics::ListSample`s. In order to be able to perform an image classification, we will need to use the `itk::Statistics::ImageToListAdaptor` which is templated over the type of image to be adapted. The `SOMClassifier` is templated over the sample type, the SOMMap type and the pixel type for the labels.

```
  typedef itk::Statistics::ListSample<PixelType> SampleType;
  typedef otb::SOMClassifier<SampleType, SOMMapType, LabelPixelType>
  ClassifierType;
```

The result of the classification will be stored on an image and saved to a file. Therefore, we define the types needed for this step.

```
  typedef otb::Image<LabelPixelType, Dimension> OutputImageType;
  typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

We can now start reading the input image and the SOM given as inputs to the program. We instantiate the readers as usual.

```
ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(imageFilename);
reader->Update();

SOMReaderType::Pointer somreader = SOMReaderType::New();
somreader->SetFileName(mapFilename);
somreader->Update();
```

The conversion of the input data from image to list sample is easily done using the adaptor.

```
SampleType::Pointer sample = SampleType::New();

itk::ImageRegionIterator<InputImageType> it(reader->GetOutput(),
                                            reader->GetOutput()->
                                            GetLargestPossibleRegion());

sample->SetMeasurementVectorSize(reader->GetOutput()->GetNumberOfComponentsPerPixel());
it.GoToBegin();

while (!it.IsAtEnd())
  {
  sample->PushBack(it.Get());
  ++it;
  }
```

The classifier can now be instantiated. The input data is set by using the `SetSample()` method and the SOM si set using the `SetMap()` method. The classification is triggered by using the `Update()` method.

```
ClassifierType::Pointer classifier = ClassifierType::New();
classifier->SetSample(sample.GetPointer());
classifier->SetMap(somreader->GetOutput());
classifier->Update();
```

Once the classification has been performed, the sample list obtained at the output of the classifier must be converted into an image. We create the image as follows :

```
OutputImageType::Pointer outputImage = OutputImageType::New();
outputImage->SetRegions(reader->GetOutput()->GetLargestPossibleRegion());
outputImage->Allocate();
```

We can now get a pointer to the classification result.

```
ClassifierType::OutputType* membershipSample = classifier->GetOutput();
```

And we can declare the iterators pointing to the front and the back of the sample list.

```
ClassifierType::OutputType::ConstIterator m_iter =  membershipSample->Begin();
ClassifierType::OutputType::ConstIterator m_last =  membershipSample->End();
```

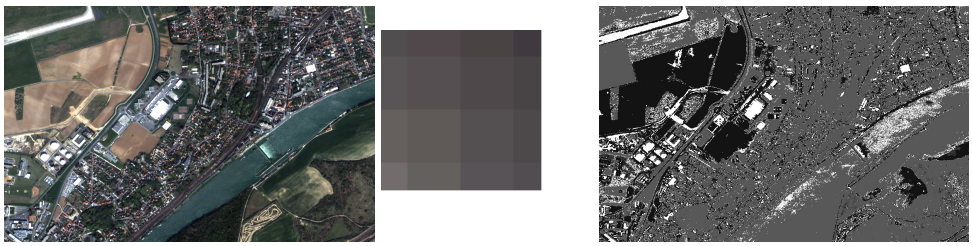


Figure 19.5: Result of the SOM learning. Left: RGB image. Center: SOM. Right: Classified Image

We also declare an `itk::ImageRegionIterator::i`n order to fill the output image with the class labels.

```
typedef itk::ImageRegionIterator<OutputImageType> OutputIteratorType;

OutputIteratorType outIt(outputImage, outputImage->GetLargestPossibleRegion());
```

We iterate through the sample list and the output image and assign the label values to the image pixels.

```
outIt.GoToBegin();

while (m_iter != m_last && !outIt.IsAtEnd())
  {
  outIt.Set(m_iter.GetClassLabel());
  ++m_iter;
  ++outIt;
  }
```

Finally, we write the classified image to a file.

```
WriterType::Pointer writer = WriterType::New();
writer->SetFileName(outputFilename);
writer->SetInput(outputImage);
writer->Update();
```

Figure 19.5 shows the result of the SOM classification.

Multi-band, streamed classification

The source code for this example can be found in the file
`Examples/Classification/SOMImageClassificationExample.cxx`.

In previous examples, we have used the `otb::SOMClassifier`, which uses the ITK classification framework. This good for compatibility with the ITK framework, but introduces the limitations of not being able to use streaming and being able to know at compilation time the number

of bands of the image to be classified. In OTB we have avoided this limitation by developing the otb::SOMImageClassificationFilter. In this example we will illustrate its use. We start by including the appropriate header file.

```
#include "otbSOMImageClassificationFilter.h"
```

We will assume double precision input images and will also define the type for the labeled pixels.

```
const unsigned int Dimension = 2;
typedef double         PixelType;
typedef unsigned short LabeledPixelType;
```

Our classifier will be genric enough to be able to process images with any number of bands. We read the images as otb::VectorImages. The labeled image will be a scalar image.

```
typedef otb::VectorImage<PixelType, Dimension>  ImageType;
typedef otb::Image<LabeledPixelType, Dimension> LabeledImageType;
```

We can now define the type for the classifier filter, which is templated over its input and output image types and the SOM type.

```
typedef otb::SOMMap<ImageType::PixelType> SOMMapType;
typedef otb::SOMImageClassificationFilter<ImageType,
    LabeledImageType,
    SOMMapType>
ClassificationFilterType;
```

And finally, we define the readers (for the input image and theSOM) and the writer. Since the images, to classify can be very big, we will use a streamed writer which will trigger the streaming ability of the classifier.

```
typedef otb::ImageFileReader<ImageType>                ReaderType;
typedef otb::ImageFileReader<SOMMapType>               SOMReaderType;
typedef otb::ImageFileWriter<LabeledImageType> WriterType;
```

We instantiate the classifier and the reader objects and we set the existing SOM obtained in a previous training step.

```
ClassificationFilterType::Pointer filter = ClassificationFilterType::New();

ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(infname);

SOMReaderType::Pointer somreader = SOMReaderType::New();
somreader->SetFileName(somfname);
somreader->Update();

filter->SetMap(somreader->GetOutput());
```

We plug the pipeline and trigger its execution by updating the output of the writer.

```
filter->SetInput(reader->GetOutput());

WriterType::Pointer writer = WriterType::New();
writer->SetInput(filter->GetOutput());
writer->SetFileName(outfname);
writer->Update();
```

19.2.3 Bayesian Plug-In Classifier

The source code for this example can be found in the file
`Examples/Classification/BayesianPluginClassifier.cxx`.

In this example, we present a system that places measurement vectors into two Gaussian classes. The Figure 19.6 shows all the components of the classifier system and the data flow. This system differs with the previous k-means clustering algorithms in several ways. The biggest difference is that this classifier uses the `itk::Statistics::itkGaussianMembershipFunction` as membership functions instead of the `itk::Statistics::EuclideanDistanceMetric`. Since the membership function is different, the membership function requires a different set of parameters, mean vectors and covariance matrices. We choose the `itk::Statistics::MeanSampleFilter` (sample mean) and the `itk::Statistics::CovarianceSampleFilter` (sample covariance) for the estimation algorithms of the two parameters. If we want more robust estimation algorithm, we can replace these estimation algorithms with more alternatives without changing other components in the classifier system.

It is a bad idea to use the same sample for test and training (parameter estimation) of the parameters. However, for simplicity, in this example, we use a sample for test and training.

We use the `itk::Statistics::ListSample` as the sample (test and training). The `itk::Vector` is our measurement vector class. To store measurement vectors into two separate sample containers, we use the `itk::Statistics::Subsample` objects.

```
#include "itkVector.h"
#include "itkArray.h"
#include "itkListSample.h"
#include "itkSubsample.h"
```

The following two files provides us the parameter estimation algorithms.

```
#include "itkMeanSampleFilter.h"
#include "itkCovarianceSampleFilter.h"
```

The following files define the components required by ITK statistical classification framework: the decision rule, the membership function, and the classifier.

```
#include "itkDecisionRule.h"
#include "itkMaximumRatioDecisionRule.h"
#include "itkGaussianMembershipFunction.h"
```

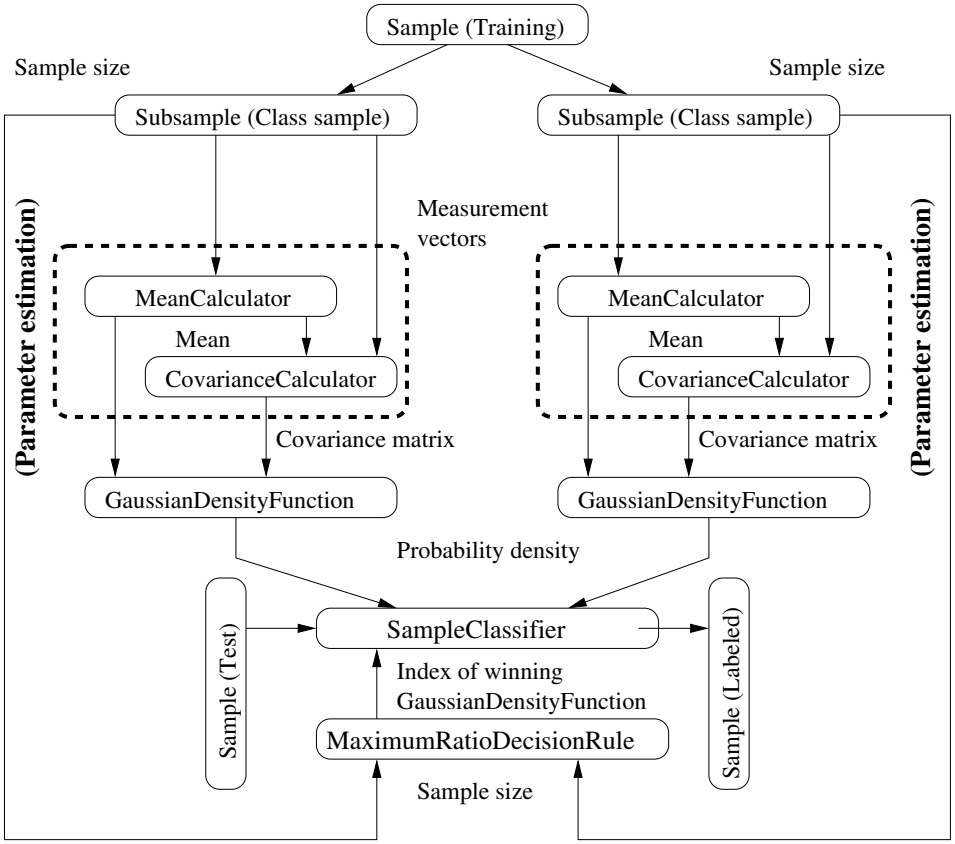


Figure 19.6: Bayesian plug-in classifier for two Gaussian classes.

```
#include "itkSampleClassifierFilter.h"
```

We will fill the sample with random variables from two normal distribution using the itk::Statistics::NormalVariateGenerator.

```
#include "itkNormalVariateGenerator.h"
```

Since the NormalVariateGenerator class only supports 1-D, we define our measurement vector type as a one component vector. We then, create a ListSample object for data inputs.

We also create two Subsample objects that will store the measurement vectors in sample into two separate sample containers. Each Subsample object stores only the measurement vectors belonging to a single class. This class sample will be used by the parameter estimation algorithms.

```
typedef itk::Vector<double,
    1>
MeasurementVectorType;
typedef itk::Statistics::ListSample<MeasurementVectorType> SampleType;
SampleType::Pointer sample = SampleType::New();
sample->SetMeasurementVectorSize(1);   // length of measurement vectors
// in the sample.

typedef itk::Statistics::Subsample<SampleType> ClassSampleType;
std::vector<ClassSampleType::Pointer> classSamples;
for (unsigned int i = 0; i < 2; ++i)
  {
  classSamples.push_back(ClassSampleType::New());
  classSamples[i]->SetSample(sample);
  }
```

The following code snippet creates a NormalVariateGenerator object. Since the random variable generator returns values according to the standard normal distribution (the mean is zero, and the standard deviation is one) before pushing random values into the sample, we change the mean and standard deviation. We want two normal (Gaussian) distribution data. We have two for loops. Each for loop uses different mean and standard deviation. Before we fill the sample with the second distribution data, we call Initialize(random seed) method, to recreate the pool of random variables in the normalGenerator. In the second for loop, we fill the two class samples with measurement vectors using the AddInstance() method.

To see the probability density plots from the two distributions, refer to Figure 19.2.

```
typedef itk::Statistics::NormalVariateGenerator NormalGeneratorType;
NormalGeneratorType::Pointer normalGenerator = NormalGeneratorType::New();

normalGenerator->Initialize(101);

MeasurementVectorType          mv;
double                         mean = 100;
double                         standardDeviation = 30;
SampleType::InstanceIdentifier id = 0UL;
for (unsigned int i = 0; i < 100; ++i)
```

```
  {
  mv.Fill((normalGenerator->GetVariate() * standardDeviation) + mean);
  sample->PushBack(mv);
  classSamples[0]->AddInstance(id);
  ++id;
  }

normalGenerator->Initialize(3024);
mean = 200;
standardDeviation = 30;
for (unsigned int i = 0; i < 100; ++i)
  {
  mv.Fill((normalGenerator->GetVariate() * standardDeviation) + mean);
  sample->PushBack(mv);
  classSamples[1]->AddInstance(id);
  ++id;
  }
```

In the following code snippet, notice that the template argument for the MeanSampleFilter and CovarianceFilter is `ClassSampleType` (i.e., type of Subsample) instead of SampleType (i.e., type of ListSample). This is because the parameter estimation algorithms are applied to the class sample.

```
typedef itk::Statistics::MeanSampleFilter<ClassSampleType> MeanEstimatorType;
typedef itk::Statistics::CovarianceSampleFilter<ClassSampleType>
CovarianceEstimatorType;

std::vector<MeanEstimatorType::Pointer>       meanEstimators;
std::vector<CovarianceEstimatorType::Pointer> covarianceEstimators;

for (unsigned int i = 0; i < 2; ++i)
  {
  meanEstimators.push_back(MeanEstimatorType::New());
  meanEstimators[i]->SetInput(classSamples[i]);
  meanEstimators[i]->Update();

  covarianceEstimators.push_back(CovarianceEstimatorType::New());
  covarianceEstimators[i]->SetInput(classSamples[i]);
  //covarianceEstimators[i]->SetMean(meanEstimators[i]->GetOutput());
  covarianceEstimators[i]->Update();
  }
```

We print out the estimated parameters.

```
for (unsigned int i = 0; i < 2; ++i)
  {
  std::cout << "class[" << i << "] " << std::endl;
  std::cout << "    estimated mean : "
            << meanEstimators[i]->GetMean()
            << "    covariance matrix : "
            << covarianceEstimators[i]->GetCovarianceMatrixOutput()->Get() << std::endl;
  }
```

After creating a SampleClassifierFilter object and a MaximumRatioDecisionRule object, we plug in the `decisionRule` and the `sample` to the classifier. Then, we specify the number of classes that will be considered using the `SetNumberOfClasses()` method.

The MaximumRatioDecisionRule requires a vector of *a priori* probability values. Such *a priori* probability will be the $P(\omega_i)$ of the following variation of the Bayes decision rule:

$$\text{Decide } \omega_i \text{ if } \frac{p(\overrightarrow{x}|\omega_i)}{p(\overrightarrow{x}|\omega_j)} > \frac{P(\omega_j)}{P(\omega_i)} \text{ for all } j \neq i \tag{19.3}$$

The remainder of the code snippet shows how to use user-specified class labels. The classification result will be stored in a MembershipSample object, and for each measurement vector, its class label will be one of the two class labels, 100 and 200 (`unsigned int`).

```
  typedef itk::Statistics::GaussianMembershipFunction
  <MeasurementVectorType> MembershipFunctionType;
  typedef itk::Statistics::MaximumRatioDecisionRule DecisionRuleType;
  DecisionRuleType::Pointer decisionRule = DecisionRuleType::New();

  DecisionRuleType::PriorProbabilityVectorType aPrioris;
  aPrioris.push_back(classSamples[0]->GetTotalFrequency()
                     / sample->GetTotalFrequency());
  aPrioris.push_back(classSamples[1]->GetTotalFrequency()
                     / sample->GetTotalFrequency());
  decisionRule->SetPriorProbabilities(aPrioris);

  typedef itk::Statistics::SampleClassifierFilter<SampleType> ClassifierType;
  ClassifierType::Pointer classifier = ClassifierType::New();

  classifier->SetDecisionRule(dynamic_cast< itk::Statistics::DecisionRule* >( decisionRule.GetPointer(
  classifier->SetInput(sample);
  classifier->SetNumberOfClasses(2);

  std::vector<long unsigned int> classLabels;
  classLabels.resize(2);
  classLabels[0] = 100;
  classLabels[1] = 200;

  typedef itk::SimpleDataObjectDecorator<std::vector<long unsigned int> >
ClassLabelDecoratedType;
  ClassLabelDecoratedType::Pointer classLabelsDecorated = ClassLabelDecoratedType::New();
  classLabelsDecorated->Set(classLabels);

  classifier->SetClassLabels(classLabelsDecorated);
```

The `classifier` is almost ready to perform the classification except that it needs two membership functions that represent the two clusters.

In this example, we can imagine that the two clusters are modeled by two Euclidean distance functions. The distance function (model) has only one parameter, the mean (centroid) set by the `SetOrigin()` method. To plug-in two distance functions, we call the `AddMembershipFunction()` method. Then invocation of the `Update()` method will perform the classification.

```
  typedef ClassifierType::MembershipFunctionType
MembershipFunctionBaseType;
  typedef ClassifierType::MembershipFunctionVectorObjectType::ComponentType
ComponentMembershipType;

  // Vector Containing the membership function used
  ComponentMembershipType     membershipFunctions;

  for (unsigned int i = 0; i < 2; i++)
    {
    MembershipFunctionType::Pointer curMemshpFunction =
MembershipFunctionType::New();
    curMemshpFunction->SetMean(meanEstimators[i]->GetMean());
    curMemshpFunction->SetCovariance(covarianceEstimators[i]->GetCovarianceMatrix());

    // cast the GaussianMembershipFunction in a
    // itk::MembershipFunctionBase
    membershipFunctions.push_back(dynamic_cast<const MembershipFunctionBaseType*
>(curMemshpFunction.GetPointer()));
    }

  ClassifierType::MembershipFunctionVectorObjectPointer membershipVectorObject = ClassifierTyp
  membershipVectorObject->Set(membershipFunctions);

  classifier->SetMembershipFunctions(membershipVectorObject);
  classifier->Update();
```

The following code snippet prints out pairs of a measurement vector and its class label in the `sample`.

```
  const ClassifierType::MembershipSampleType* membershipSample = classifier->GetOutput();
  ClassifierType::MembershipSampleType::ConstIterator iter = membershipSample->Begin();

  while (iter != membershipSample->End())
    {
    std::cout << "measurement vector = " << iter.GetMeasurementVector()
              << "class label = " << iter.GetClassLabel() << std::endl;
    ++iter;
    }
```

19.2.4 Expectation Maximization Mixture Model Estimation

The source code for this example can be found in the file `Examples/Classification/ExpectationMaximizationMixtureModelEstimator.cxx`.

In this example, we present ITK's implementation of the expectation maximization (EM) process to generate parameter estimates for a two Gaussian component mixture model.

The Bayesian plug-in classifier example (see Section 19.2.3) used two Gaussian probability density functions (PDF) to model two Gaussian distribution classes (two models for two class). However, in

some cases, we want to model a distribution as a mixture of several different distributions. Therefore, the probability density function ($p(x)$) of a mixture model can be stated as follows :

$$p(x) = \sum_{i=0}^{c} \alpha_i f_i(x) \tag{19.4}$$

where i is the index of the component, c is the number of components, α_i is the proportion of the component, and f_i is the probability density function of the component.

Now the task is to find the parameters(the component PDF's parameters and the proportion values) to maximize the likelihood of the parameters. If we know which component a measurement vector belongs to, the solutions to this problem is easy to solve. However, we don't know the membership of each measurement vector. Therefore, we use the expectation of membership instead of the exact membership. The EM process splits into two steps:

1. E step: calculate the expected membership values for each measurement vector to each classes.
2. M step: find the next parameter sets that maximize the likelihood with the expected membership values and the current set of parameters.

The E step is basically a step that calculates the *a posteriori* probability for each measurement vector.

The M step is dependent on the type of each PDF. Most of distributions belonging to exponential family such as Poisson, Binomial, Exponential, and Normal distributions have analytical solutions for updating the parameter set. The `itk::Statistics::ExpectationMaximizationMixtureModelEstimator` class assumes that such type of components.

In the following example we use the `itk::Statistics::ListSample` as the sample (test and training). The `itk::Vector::is` our measurement vector class. To store measurement vectors into two separate sample container, we use the `itk::Statistics::Subsample` objects.

```
#include "itkVector.h"
#include "itkListSample.h"
```

The following two files provide us the parameter estimation algorithms.

```
#include "itkGaussianMixtureModelComponent.h"
#include "itkExpectationMaximizationMixtureModelEstimator.h"
```

We will fill the sample with random variables from two normal distribution using the `itk::Statistics::NormalVariateGenerator`.

```
#include "itkNormalVariateGenerator.h"
```

Since the NormalVariateGenerator class only supports 1-D, we define our measurement vector type as a one component vector. We then, create a ListSample object for data inputs.

We also create two Subsample objects that will store the measurement vectors in the `sample` into two separate sample containers. Each Subsample object stores only the measurement vectors belonging to a single class. This *class sample* will be used by the parameter estimation algorithms.

```
unsigned int numberOfClasses = 2;
typedef itk::Vector<double,
    1>
MeasurementVectorType;
typedef itk::Statistics::ListSample<MeasurementVectorType> SampleType;
SampleType::Pointer sample = SampleType::New();
sample->SetMeasurementVectorSize(1);   // length of measurement vectors
// in the sample.
```

The following code snippet creates a NormalVariateGenerator object. Since the random variable generator returns values according to the standard normal distribution (the mean is zero, and the standard deviation is one) before pushing random values into the `sample`, we change the mean and standard deviation. We want two normal (Gaussian) distribution data. We have two for loops. Each for loop uses different mean and standard deviation. Before we fill the `sample` with the second distribution data, we call `Initialize()` method to recreate the pool of random variables in the `normalGenerator`. In the second for loop, we fill the two class samples with measurement vectors using the `AddInstance()` method.

To see the probability density plots from the two distribution, refer to Figure 19.2.

```
typedef itk::Statistics::NormalVariateGenerator NormalGeneratorType;
NormalGeneratorType::Pointer normalGenerator = NormalGeneratorType::New();

normalGenerator->Initialize(101);

MeasurementVectorType mv;
double                mean = 100;
double                standardDeviation = 30;
for (unsigned int i = 0; i < 100; ++i)
  {
  mv[0] = (normalGenerator->GetVariate() * standardDeviation) + mean;
  sample->PushBack(mv);
  }

normalGenerator->Initialize(3024);
mean = 200;
standardDeviation = 30;
for (unsigned int i = 0; i < 100; ++i)
  {
  mv[0] = (normalGenerator->GetVariate() * standardDeviation) + mean;
  sample->PushBack(mv);
  }
```

In the following code snippet notice that the template argument for the MeanSampleFilter and CovarianceSampleFilter is `ClassSampleType` (i.e., type of Subsample) instead of `SampleType` (i.e., type of ListSample). This is because the parameter estimation algorithms are applied to the class sample.

```
typedef itk::Array<double> ParametersType;
ParametersType params(2);

std::vector<ParametersType> initialParameters(numberOfClasses);
params[0] = 110.0;
params[1] = 800.0;
initialParameters[0] = params;

params[0] = 210.0;
params[1] = 850.0;
initialParameters[1] = params;

typedef itk::Statistics::GaussianMixtureModelComponent<SampleType>
ComponentType;

std::vector<ComponentType::Pointer> components;
for (unsigned int i = 0; i < numberOfClasses; ++i)
  {
  components.push_back(ComponentType::New());
  (components[i])->SetSample(sample);
  (components[i])->SetParameters(initialParameters[i]);
  }
```

We run the estimator.

```
typedef itk::Statistics::ExpectationMaximizationMixtureModelEstimator<
    SampleType> EstimatorType;
EstimatorType::Pointer estimator = EstimatorType::New();

estimator->SetSample(sample);
estimator->SetMaximumIteration(200);

itk::Array<double> initialProportions(numberOfClasses);
initialProportions[0] = 0.5;
initialProportions[1] = 0.5;

estimator->SetInitialProportions(initialProportions);

for (unsigned int i = 0; i < numberOfClasses; ++i)
  {
  estimator->AddComponent((ComponentType::Superclass*)
                          (components[i]).GetPointer());
  }

estimator->Update();
```

We then print out the estimated parameters.

```
for (unsigned int i = 0; i < numberOfClasses; ++i)
  {
  std::cout << "Cluster[" << i << "]" << std::endl;
  std::cout << "    Parameters:" << std::endl;
  std::cout << "          " << (components[i])->GetFullParameters()
```

```
            << std::endl;
  std::cout << "    Proportion: ";
  std::cout << "          " << (estimator->GetProportions())[i] << std::endl;
  }
```

19.2.5 Statistical Segmentations

Stochastic Expectation Maximization

The Stochastic Expectation Maximization (SEM) approach is a stochastic version of the EM mixture estimation seen on section 19.2.4. It has been introduced by [22] to prevent convergence of the EM approach from local minima. It avoids the analytical maximization issued by integrating a stochastic sampling procedure in the estimation process. It induces an almost sure (a.s.) convergence to the algorithm.

From the initial two step formulation of the EM mixture estimation, the SEM may be decomposed into 3 steps:

1. **E-step**, calculates the expected membership values for each measurement vector to each classes.
2. **S-step**, performs a stochastic sampling of the membership vector to each classes, according to the membership values computed in the E-step.
3. **M-step**, updates the parameters of the membership probabilities (parameters to be defined through the class `itk::Statistics::ModelComponentBase` and its inherited classes).

The implementation of the SEM has been turned to a contextual SEM in the sense where the evaluation of the membership parameters is conditioned to membership values of the spatial neighborhood of each pixels.

The source code for this example can be found in the file `Examples/Learning/SEMModelEstimatorExample.cxx`.

In this example, we present OTB's implementation of SEM, through the class `otb::SEMClassifier`. This class performs a stochastic version of the EM algorithm, but instead of inheriting from `itk::ExpectationMaximizationMixtureModelEstimator`, we choosed to inherit from `itk::Statistics::ListSample< TSample >`, in the same way as `otb::SVMClassifier`.

The program begins with `otb::VectorImage` and outputs `itb::Image`. Then appropriate header files have to be included:

```
#include "otbImage.h"
#include "otbVectorImage.h"
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
```

otb::SEMClassifier performs estimation of mixture to fit the initial histogram. Actually, mixture of Gaussian pdf can be performed. Those generic pdf are treated in otb::Statistics::ModelComponentBase. The Gaussian model is taken in charge with the class otb::Statistics::GaussianModelComponent.

```
#include "otbGaussianModelComponent.h"
#include "otbSEMClassifier.h"
```

Input/Output images type are define in a classical way. In fact, a itk::VariableLengthVector is to be considered for the templated MeasurementVectorType, which will be used in the ListSample interface.

```
    typedef double PixelType;

    typedef otb::VectorImage<PixelType, 2>  ImageType;
    typedef otb::ImageFileReader<ImageType> ReaderType;

    typedef otb::Image<unsigned char, 2>          OutputImageType;
    typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

Once the input image is opened, the classifier may be initialised by SmartPointer.

```
    typedef otb::SEMClassifier<ImageType, OutputImageType> ClassifType;
    ClassifType::Pointer classifier = ClassifType::New();
```

Then, it follows, classical initializations of the pipeline.

```
    classifier->SetNumberOfClasses(numberOfClasses);
    classifier->SetMaximumIteration(numberOfIteration);
    classifier->SetNeighborhood(neighborhood);
    classifier->SetTerminationThreshold(terminationThreshold);
    classifier->SetSample(reader->GetOutput());
```

When an initial segmentation is available, the classifier may use it as image (of type OutputImageType) or as a itk::SampleClassifier result (of type itk::Statistics::MembershipSample< SampleType >).

```
    if (fileNameImgInit != NULL)
      {
      typedef otb::ImageFileReader<OutputImageType> ImgInitReaderType;
      ImgInitReaderType::Pointer segReader = ImgInitReaderType::New();
      segReader->SetFileName(fileNameImgInit);
      segReader->Update();
      classifier->SetClassLabels(segReader->GetOutput());
      }
```

By default, otb::SEMClassifier performs initialization of ModelComponentBase by as many instanciation of otb::Statistics::GaussianModelComponent as the number of classes to estimate in the mixture. Nevertheless, the user may add specific distribution into the mixture estimation. It is permitted by the use of AddComponent for the given class number and the specific distribution.

```
typedef ClassifType::ClassSampleType ClassSampleType;
typedef otb::Statistics::GaussianModelComponent<ClassSampleType>
GaussianType;

for (int i = 0; i < numberOfClasses; ++i)
  {
  GaussianType::Pointer model = GaussianType::New();
  classifier->AddComponent(i, model);
  }
```

Once the pipeline is instanciated. The segmentation by itself may be launched by using the `Update` function.

```
try
  {
  classifier->Update();
  }
```

The segmentation may outputs a result of type `itk::Statistics::MembershipSample< SampleType >` as it is the case for the `otb::SVMClassifier`. But when using `GetOutputImage` the output is directly an Image.

Only for visualization purposes, we choose to rescale the image of classes before saving it to a file. We will use the `itk::RescaleIntensityImageFilter` for this purpose.

```
typedef itk::RescaleIntensityImageFilter<OutputImageType,
    OutputImageType> RescalerType;
RescalerType::Pointer rescaler = RescalerType::New();

rescaler->SetOutputMinimum(itk::NumericTraits<unsigned char>::min());
rescaler->SetOutputMaximum(itk::NumericTraits<unsigned char>::max());

rescaler->SetInput(classifier->GetOutputImage());

WriterType::Pointer writer = WriterType::New();
writer->SetFileName(fileNameOut);
writer->SetInput(rescaler->GetOutput());
writer->Update();
```

Figure 19.7 shows the result of the SEM segmentation with 4 different classes and a contextual neighborhood of 3 pixels.

As soon as the segmentation is performed by an iterative stochastic process, it is worth verifying the output status: does the segmentation ends when it has converged or just at the limit of the iteration numbers.

```
std::cerr << "Program terminated with a ";
if (classifier->GetTerminationCode() ==
    ClassifType::CONVERGED) std::cerr << "converged ";
else std::cerr << "not-converged ";
std::cerr << "code...\n";
```

Figure 19.7: SEM Classification results.

The text output gives for each class the parameters of the pdf (e.g. mean of each component of the class and there covariance matrix, in the case of a Gaussian mixture model).

```
classifier->Print(std::cerr);
```

19.2.6 Classification using Markov Random Fields

Markov Random Fields are probabilistic models that use the statistical dependency between pixels in a neighborhood to infeer the value of a give pixel.

ITK framework

The `itk::Statistics::MRFImageFilter` uses the maximum a posteriori (MAP) estimates for modeling the MRF. The object traverses the data set and uses the model generated by the Mahalanobis distance classifier to get the the distance between each pixel in the data set to a set of known classes, updates the distances by evaluating the influence of its neighboring pixels (based on a MRF model) and finally, classifies each pixel to the class which has the minimum distance to that pixel (taking the neighborhood influence under consideration). The energy function minimization is done using the iterated conditional modes (ICM) algorithm [12].

The source code for this example can be found in the file
`Examples/Classification/ScalarImageMarkovRandomField1.cxx`.

This example shows how to use the Markov Random Field approach for classifying the pixel of a scalar image.

The `itk::Statistics::MRFImageFilter` is used for refining an initial classification by intro-

ducing the spatial coherence of the labels. The user should provide two images as input. The first image is the one to be classified while the second image is an image of labels representing an initial classification.

The following headers are related to reading input images, writing the output image, and making the necessary conversions between scalar and vector images.

```
#include "otbImage.h"
#include "itkFixedArray.h"
#include "otbImageFileReader.h"
#include "otbImageFileWriter.h"
#include "itkComposeImageFilter.h"
```

The following headers are related to the statistical classification classes.

```
#include "itkMRFImageFilter.h"
#include "itkDistanceToCentroidMembershipFunction.h"
#include "itkMinimumDecisionRule.h"
#include "itkImageClassifierBase.h"
```

First we define the pixel type and dimension of the image that we intend to classify. With this image type we can also declare the `otb::ImageFileReader` needed for reading the input image, create one and set its input filename.

```
typedef unsigned char PixelType;
const unsigned int Dimension = 2;

typedef otb::Image<PixelType, Dimension> ImageType;

typedef otb::ImageFileReader<ImageType> ReaderType;
ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(inputImageFileName);
```

As a second step we define the pixel type and dimension of the image of labels that provides the initial classification of the pixels from the first image. This initial labeled image can be the output of a K-Means method like the one illustrated in section 19.2.1.

```
typedef unsigned char LabelPixelType;

typedef otb::Image<LabelPixelType, Dimension> LabelImageType;

typedef otb::ImageFileReader<LabelImageType> LabelReaderType;
LabelReaderType::Pointer labelReader = LabelReaderType::New();
labelReader->SetFileName(inputLabelImageFileName);
```

Since the Markov Random Field algorithm is defined in general for images whose pixels have multiple components, that is, images of vector type, we must adapt our scalar image in order to satisfy the interface expected by the `MRFImageFilter`. We do this by using the `itk::ScalarToArrayCastImageFilter`. With this filter we will present our scalar image as a vector image whose vector pixels contain a single component.

```
typedef itk::FixedArray<LabelPixelType, 1> ArrayPixelType;

typedef otb::Image<ArrayPixelType, Dimension> ArrayImageType;

typedef itk::ComposeImageFilter<
    ImageType, ArrayImageType> ScalarToArrayFilterType;

ScalarToArrayFilterType::Pointer
  scalarToArrayFilter = ScalarToArrayFilterType::New();
scalarToArrayFilter->SetInput(0, reader->GetOutput());
```

With the input image type `ImageType` and labeled image type `LabelImageType` we instantiate the type of the `itk::MRFImageFilter` that will apply the Markov Random Field algorithm in order to refine the pixel classification.

```
typedef itk::MRFImageFilter<ArrayImageType, LabelImageType> MRFFilterType;

MRFFilterType::Pointer mrfFilter = MRFFilterType::New();

mrfFilter->SetInput(scalarToArrayFilter->GetOutput());
```

We set now some of the parameters for the MRF filter. In particular, the number of classes to be used during the classification, the maximum number of iterations to be run in this filter and the error tolerance that will be used as a criterion for convergence.

```
mrfFilter->SetNumberOfClasses(numberOfClasses);
mrfFilter->SetMaximumNumberOfIterations(numberOfIterations);
mrfFilter->SetErrorTolerance(1e-7);
```

The smoothing factor represents the tradeoff between fidelity to the observed image and the smoothness of the segmented image. Typical smoothing factors have values between 1 5. This factor will multiply the weights that define the influence of neighbors on the classification of a given pixel. The higher the value, the more uniform will be the regions resulting from the classification refinement.

```
mrfFilter->SetSmoothingFactor(smoothingFactor);
```

Given that the MRF filter needs to continually relabel the pixels, it needs access to a set of membership functions that will measure to what degree every pixel belongs to a particular class. The classification is performed by the `itk::ImageClassifierBase` class, that is instantiated using the type of the input vector image and the type of the labeled image.

```
typedef itk::ImageClassifierBase<
    ArrayImageType,
    LabelImageType>   SupervisedClassifierType;

SupervisedClassifierType::Pointer classifier =
  SupervisedClassifierType::New();
```

The classifier needs a decision rule to be set by the user. Note that we must use `GetPointer()` in the call of the `SetDecisionRule()` method because we are passing a SmartPointer, and smart pointer cannot perform polymorphism, we must then extract the raw pointer that is associated to the smart pointer. This extraction is done with the GetPointer() method.

```
typedef itk::Statistics::MinimumDecisionRule DecisionRuleType;

DecisionRuleType::Pointer classifierDecisionRule = DecisionRuleType::New();

classifier->SetDecisionRule(classifierDecisionRule.GetPointer());
```

We now instantiate the membership functions. In this case we use the `itk::Statistics::DistanceToCentroidMembershipFunction` class templated over the pixel type of the vector image, which in our example happens to be a vector of dimension 1.

```
typedef itk::Statistics::DistanceToCentroidMembershipFunction<
    ArrayPixelType>
MembershipFunctionType;

typedef MembershipFunctionType::Pointer MembershipFunctionPointer;

double             meanDistance = 0;
MembershipFunctionType::CentroidType centroid(reader->GetOutput()->GetNumberOfComponentsPerP
for (unsigned int i = 0; i < numberOfClasses; ++i)
  {
  MembershipFunctionPointer membershipFunction =
    MembershipFunctionType::New();

  membershipFunction->SetMeasurementVectorSize(reader->GetOutput()->GetNumberOfComponentsPer
  centroid[0] = atof(argv[i + numberOfArgumentsBeforeMeans]);

  membershipFunction->SetCentroid(centroid);

  classifier->AddMembershipFunction(membershipFunction);
  meanDistance += static_cast<double> (centroid[0]);
  }
meanDistance /= numberOfClasses;
```

and we set the neighborhood radius that will define the size of the clique to be used in the computation of the neighbors' influence in the classification of any given pixel. Note that despite the fact that we call this a radius, it is actually the half size of an hypercube. That is, the actual region of influence will not be circular but rather an N-Dimensional box. For example, a neighborhood radius of 2 in a 3D image will result in a clique of size 5x5x5 pixels, and a radius of 1 will result in a clique of size 3x3x3 pixels.

```
mrfFilter->SetNeighborhoodRadius(1);
```

We should now set the weights used for the neighbors. This is done by passing an array of values that contains the linear sequence of weights for the neighbors. For example, in a neighborhood of size 3x3x3, we should provide a linear array of 9 weight values. The values are packaged in a

std::vector and are supposed to be double. The following lines illustrate a typical set of values for a 3x3x3 neighborhood. The array is arranged and then passed to the filter by using the method SetMRFNeighborhoodWeight().

```
std::vector<double> weights;
weights.push_back(1.5);
weights.push_back(2.0);
weights.push_back(1.5);
weights.push_back(2.0);
weights.push_back(0.0); // This is the central pixel
weights.push_back(2.0);
weights.push_back(1.5);
weights.push_back(2.0);
weights.push_back(1.5);
```

We now scale weights so that the smoothing function and the image fidelity functions have comparable value. This is necessary since the label image and the input image can have different dynamic ranges. The fidelity function is usually computed using a distance function, such as the itk::DistanceToCentroidMembershipFunction or one of the other membership functions. They tend to have values in the order of the means specified.

```
double totalWeight = 0;
for (std::vector<double>::const_iterator wcIt = weights.begin();
     wcIt != weights.end(); ++wcIt)
  {
  totalWeight += *wcIt;
  }
for (std::vector<double>::iterator wIt = weights.begin();
     wIt != weights.end(); wIt++)
  {
  *wIt = static_cast<double> ((*wIt) * meanDistance / (2 * totalWeight));
  }

mrfFilter->SetMRFNeighborhoodWeight(weights);
```

Finally, the classifier class is connected to the Markov Random Fields filter.

```
mrfFilter->SetClassifier(classifier);
```

The output image produced by the itk::MRFImageFilter has the same pixel type as the labeled input image. In the following lines we use the OutputImageType in order to instantiate the type of a otb::ImageFileWriter. Then create one, and connect it to the output of the classification filter after passing it through an intensity rescaler to rescale it to an 8 bit dynamic range

```
typedef MRFFilterType::OutputImageType OutputImageType;
```

```
typedef otb::ImageFileWriter<OutputImageType> WriterType;

WriterType::Pointer writer = WriterType::New();

writer->SetInput(intensityRescaler->GetOutput());
```

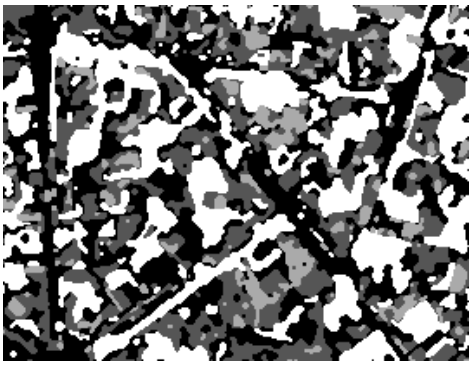


Figure 19.8: Effect of the MRF filter.

```
writer->SetFileName(outputImageFileName);
```

We are now ready for triggering the execution of the pipeline. This is done by simply invoking the `Update()` method in the writer. This call will propagate the update request to the reader and then to the MRF filter.

```
try
  {
  writer->Update();
  }
catch (itk::ExceptionObject& excp)
  {
  std::cerr << "Problem encountered while writing ";
  std::cerr << " image file : " << argv[2] << std::endl;
  std::cerr << excp << std::endl;
  return EXIT_FAILURE;
  }
```

Figure 19.8 illustrates the effect of this filter with four classes. In this example the filter was run with a smoothing factor of 3. The labeled image was produced by ScalarImageKmeansClassifier.cxx and the means were estimated by ScalarImageKmeansModelEstimator.cxx described in section 19.2.1. The obtained result can be compared with the one of figure 19.1 to see the interest of using the MRF approach in order to ensure the regularization of the classified image.

OTB framework

The ITK approach was considered not to be flexible enough for some remote sensing applications. Therefore, we decided to implement our own framework.

The source code for this example can be found in the file

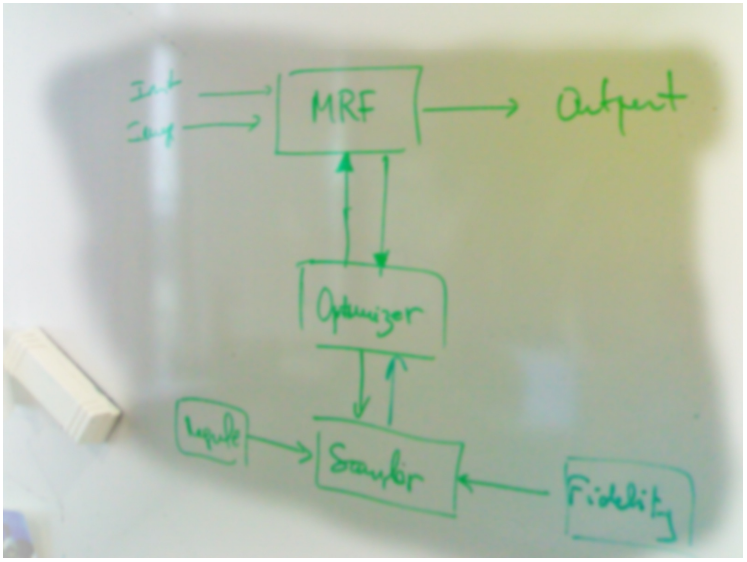


Figure 19.9: OTB Markov Framework.

Examples/Markov/MarkovClassification1Example.cxx.

This example illustrates the details of the otb::MarkovRandomFieldFilter. This filter is an application of the Markov Random Fields for classification, segmentation or restauration.

This example applies the otb::MarkovRandomFieldFilter to classify an image into four classes defined by their mean and variance. The optimization is done using an Metropolis algorithm with a random sampler. The regularization energy is defined by a Potts model and the fidelity by a Gaussian model.

The first step toward the use of this filter is the inclusion of the proper header files.

```
#include "otbMRFEnergyPotts.h"
#include "otbMRFEnergyGaussianClassification.h"
#include "otbMRFOptimizerMetropolis.h"
#include "otbMRFSamplerRandom.h"
```

Then we must decide what pixel type to use for the image. We choose to make all computations with double precision. The labelled image is of type unsigned char which allows up to 256 different classes.

```
  const unsigned int Dimension = 2;

  typedef double                                    InternalPixelType;
  typedef unsigned char                             LabelledPixelType;
  typedef otb::Image<InternalPixelType, Dimension> InputImageType;
  typedef otb::Image<LabelledPixelType, Dimension> LabelledImageType;
```

We define a reader for the image to be classified, an initialization for the classification (which could be random) and a writer for the final classification.

```
typedef otb::ImageFileReader<InputImageType>    ReaderType;
typedef otb::ImageFileWriter<LabelledImageType> WriterType;

ReaderType::Pointer reader = ReaderType::New();
WriterType::Pointer writer = WriterType::New();

const char * inputFilename  = argv[1];
const char * outputFilename = argv[2];

reader->SetFileName(inputFilename);
writer->SetFileName(outputFilename);
```

Finally, we define the different classes necessary for the Markov classification. A `otb::MarkovRandomFieldFilter` is instanciated, this is the main class which connect the other to do the Markov classification.

```
typedef otb::MarkovRandomFieldFilter
<InputImageType, LabelledImageType> MarkovRandomFieldFilterType;
```

An `otb::MRFSamplerRandomMAP`, which derives from the `otb::MRFSampler`, is instanciated. The sampler is in charge of proposing a modification for a given site. The `otb::MRFSamplerRandomMAP`, randomly pick one possible value according to the MAP probability.

```
typedef otb::MRFSamplerRandom<InputImageType, LabelledImageType> SamplerType;
```

An `otb::MRFOptimizerMetropoli`, which derives from the `otb::MRFOptimizer`, is instanciated. The optimizer is in charge of accepting or rejecting the value proposed by the sampler. The `otb::MRFSamplerRandomMAP`, accept the proposal according to the variation of energy it causes and a temperature parameter.

```
typedef otb::MRFOptimizerMetropolis OptimizerType;
```

Two energy, deriving from the `otb::MRFEnergy` class need to be instanciated. One energy is required for the regularization, taking into account the relashionship between neighborhing pixels in the classified image. Here it is done with the `otb::MRFEnergyPotts` which implement a Potts model.

The second energy is for the fidelity to the original data. Here it is done with an `otb::MRFEnergyGaussianClassification` class, which defines a gaussian model for the data.

```
typedef otb::MRFEnergyPotts
<LabelledImageType, LabelledImageType>  EnergyRegularizationType;
typedef otb::MRFEnergyGaussianClassification
<InputImageType, LabelledImageType>  EnergyFidelityType;
```

The different filters composing our pipeline are created by invoking their `New()` methods, assigning the results to smart pointers.

```
MarkovRandomFieldFilterType::Pointer markovFilter =
  MarkovRandomFieldFilterType::New();
EnergyRegularizationType::Pointer energyRegularization =
  EnergyRegularizationType::New();
EnergyFidelityType::Pointer energyFidelity = EnergyFidelityType::New();
OptimizerType::Pointer      optimizer = OptimizerType::New();
SamplerType::Pointer        sampler = SamplerType::New();
```

Parameter for the `otb::MRFEnergyGaussianClassification` class, meand and standard deviation are created.

```
unsigned int nClass = 4;
energyFidelity->SetNumberOfParameters(2 * nClass);
EnergyFidelityType::ParametersType parameters;
parameters.SetSize(energyFidelity->GetNumberOfParameters());
parameters[0] = 10.0; //Class 0 mean
parameters[1] = 10.0; //Class 0 stdev
parameters[2] = 80.0; //Class 1 mean
parameters[3] = 10.0; //Class 1 stdev
parameters[4] = 150.0; //Class 2 mean
parameters[5] = 10.0; //Class 2 stdev
parameters[6] = 220.0; //Class 3 mean
parameters[7] = 10.0; //Class 3 stde
energyFidelity->SetParameters(parameters);
```

Parameters are given to the different class an the sampler, optimizer and energies are connected with the Markov filter.

```
OptimizerType::ParametersType param(1);
param.Fill(atof(argv[5]));
optimizer->SetParameters(param);
markovFilter->SetNumberOfClasses(nClass);
markovFilter->SetMaximumNumberOfIterations(atoi(argv[4]));
markovFilter->SetErrorTolerance(0.0);
markovFilter->SetLambda(atof(argv[3]));
markovFilter->SetNeighborhoodRadius(1);

markovFilter->SetEnergyRegularization(energyRegularization);
markovFilter->SetEnergyFidelity(energyFidelity);
markovFilter->SetOptimizer(optimizer);
markovFilter->SetSampler(sampler);
```

The pipeline is connected. An `itk::RescaleIntensityImageFilter` rescale the classified image before saving it.

```
markovFilter->SetInput(reader->GetOutput());

typedef itk::RescaleIntensityImageFilter
<LabelledImageType, LabelledImageType> RescaleType;
RescaleType::Pointer rescaleFilter = RescaleType::New();
rescaleFilter->SetOutputMinimum(0);
rescaleFilter->SetOutputMaximum(255);
```

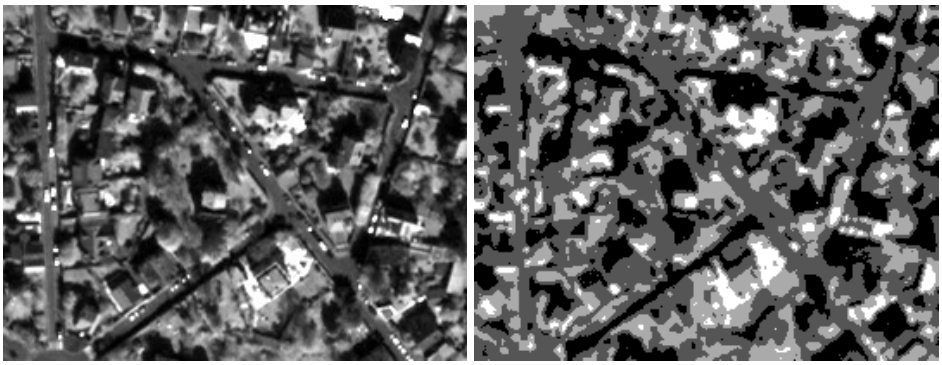


Figure 19.10: Result of applying the `otb::MarkovRandomFieldFilter` to an extract from a PAN Quickbird image for classification. The result is obtained after 20 iterations with a random sampler and a Metropolis optimizer. From left to right : original image, classification.

```
rescaleFilter->SetInput(markovFilter->GetOutput());

writer->SetInput(rescaleFilter->GetOutput());
```

Finally, the pipeline execution is trigerred.

```
writer->Update();
```

Figure 19.10 shows the output of the Markov Random Field classification after 20 iterations with a random sampler and a Metropolis optimizer.

The source code for this example can be found in the file `Examples/Markov/MarkovClassification2Example.cxx`.

Using a similar structure as the previous program and the same energy function, we are now going to slightly alter the program to use a different sampler and optimizer. The proposed sample is proposed randomly according to the MAP probability and the optimizer is the ICM which accept the proposed sample if it enable a reduction of the energy.

First, we need to include header specific to these class:

```
#include "otbMRFSamplerRandomMAP.h"
#include "otbMRFOptimizerICM.h"
```

And to declare these new type:

```
  typedef otb::MRFSamplerRandomMAP<InputImageType,
      LabelledImageType> SamplerType;
//   typedef otb::MRFSamplerRandom< InputImageType, LabelledImageType> SamplerType;
```

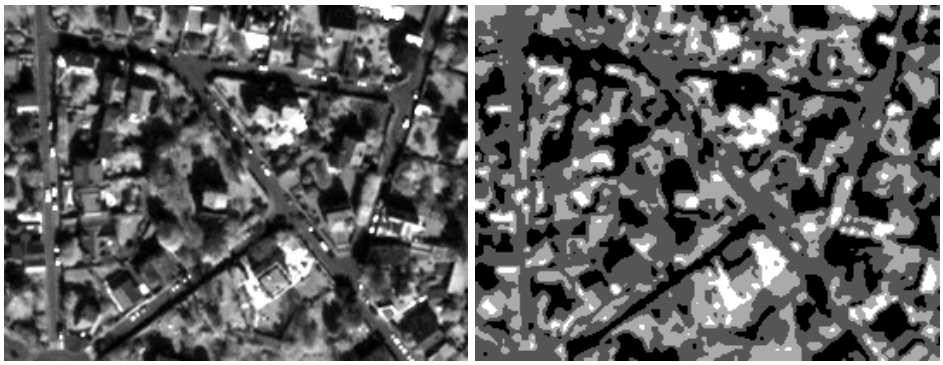


Figure 19.11: Result of applying the `otb::MarkovRandomFieldFilter` to an extract from a PAN Quickbird image for classification. The result is obtained after 5 iterations with a MAP random sampler and an ICM optimizer. From left to right : original image, classification.

```
typedef otb::MRFOptimizerICM OptimizerType;
```

As the `otb::MRFOptimizerICM` does not have any parameters, the call to `optimizer->SetParameters()` must be removed

Apart from these, no further modification is required.

Figure 19.11 shows the output of the Markov Random Field classification after 5 iterations with a MAP random sampler and an ICM optimizer.

The source code for this example can be found in the file
`Examples/Markov/MarkovClassification3Example.cxx`.

This example illustrates the details of the MarkovRandomFieldFilter by using the Fisher distribution to model the likelihood energy. This filter is an application of the Markov Random Fields for classification.

This example applies the MarkovRandomFieldFilter to classify an image into four classes defined by their Fisher distribution parameters L, M and mu. The optimization is done using a Metropolis algorithm with a random sampler. The regularization energy is defined by a Potts model and the fidelity or likelihood energy is modelled by a Fisher distribution. The parameter of the Fisher distribution was determined for each class in a supervised step. (See the File OtbParameterEstimatioOfFisherDistribution) This example is a contribution from Jan Wegner.

Then we must decide what pixel type to use for the image. We choose to make all computations with double precision. The labeled image is of type unsigned char which allows up to 256 different classes.

```
const unsigned int Dimension = 2;
typedef double        InternalPixelType;
```

```
typedef unsigned char LabelledPixelType;

typedef otb::Image<InternalPixelType, Dimension>    InputImageType;
typedef otb::Image<LabelledPixelType, Dimension>    LabelledImageType;
```

We define a reader for the image to be classified, an initialization for the classification (which could be random) and a writer for the final classification.

```
typedef otb::ImageFileReader< InputImageType >              ReaderType;
typedef otb::ImageFileWriter< LabelledImageType >  WriterType;

ReaderType::Pointer reader = ReaderType::New();
WriterType::Pointer writer = WriterType::New();
```

Finally, we define the different classes necessary for the Markov classification. A MarkovRandomFieldFilter is instantiated, this is the main class which connect the other to do the Markov classification.

```
typedef otb::MarkovRandomFieldFilter
    <InputImageType, LabelledImageType> MarkovRandomFieldFilterType;
```

An MRFSamplerRandomMAP, which derives from the MRFSampler, is instanciated. The sampler is in charge of proposing a modification for a given site. The MRFSamplerRandomMAP, randomly pick one possible value according to the MAP probability.

```
typedef otb::MRFSamplerRandom< InputImageType, LabelledImageType> SamplerType;
```

An MRFOptimizerMetropolis, which derives from the MRFOptimizer, is instanciated. The optimizer is in charge of accepting or rejecting the value proposed by the sampler. The MRFSamplerRandomMAP, accept the proposal according to the variation of energy it causes and a temperature parameter.

```
typedef otb::MRFOptimizerMetropolis OptimizerType;
```

Two energy, deriving from the MRFEnergy class need to be instantiated. One energy is required for the regularization, taking into account the relationship between neighboring pixels in the classified image. Here it is done with the MRFEnergyPotts, which implements a Potts model.

The second energy is used for the fidelity to the original data. Here it is done with a MRFEnergyFisherClassification class, which defines a Fisher distribution to model the data.

```
typedef otb::MRFEnergyPotts
    <LabelledImageType, LabelledImageType>  EnergyRegularizationType;
typedef otb::MRFEnergyFisherClassification
    <InputImageType, LabelledImageType>     EnergyFidelityType;
```

The different filters composing our pipeline are created by invoking their New() methods, assigning the results to smart pointers.

```
MarkovRandomFieldFilterType::Pointer markovFilter = MarkovRandomFieldFilterType::New();
EnergyRegularizationType::Pointer energyRegularization = EnergyRegularizationType::New();
EnergyFidelityType::Pointer energyFidelity = EnergyFidelityType::New();
OptimizerType::Pointer optimizer = OptimizerType::New();
SamplerType::Pointer sampler = SamplerType::New();
```

Parameter for the MRFEnergyFisherClassification class are created. The shape parameters M, L and the weighting parameter mu are computed in a supervised step

```
unsigned int nClass =4;
energyFidelity->SetNumberOfParameters(3*nClass);
EnergyFidelityType::ParametersType parameters;
parameters.SetSize(energyFidelity->GetNumberOfParameters());
//Class 0
parameters[0] =          12.353042;     //Class 0 mu
parameters[1] =          2.156422;        //Class 0 L
parameters[2] =          4.920403;        //Class 0 M
//Class 1
parameters[3] =          72.068291;     //Class 1 mu
parameters[4] =          11.000000;    //Class 1 L
parameters[5] =          50.950001;     //Class 1 M
//Class 2
parameters[6] =          146.665985;    //Class 2 mu
parameters[7] =          11.000000;    //Class 2 L
parameters[8] =          50.900002;     //Class 2 M
//Class 3
parameters[9]  =       200.010132;      //Class 3 mu
parameters[10] =       11.000000;       //Class 3 L
parameters[11] =       50.950001;       //Class 3 M

energyFidelity->SetParameters(parameters);
```

Parameters are given to the different classes and the sampler, optimizer and energies are connected with the Markov filter.

```
OptimizerType::ParametersType param(1);
param.Fill(atof(argv[6]));
optimizer->SetParameters(param);
markovFilter->SetNumberOfClasses(nClass);
markovFilter->SetMaximumNumberOfIterations(atoi(argv[5]));
markovFilter->SetErrorTolerance(0.0);
markovFilter->SetLambda(atof(argv[4]));
markovFilter->SetNeighborhoodRadius(1);

markovFilter->SetEnergyRegularization(energyRegularization);
markovFilter->SetEnergyFidelity(energyFidelity);
markovFilter->SetOptimizer(optimizer);
markovFilter->SetSampler(sampler);
```

The pipeline is connected. An itkRescaleIntensityImageFilter rescales the classified image before saving it.

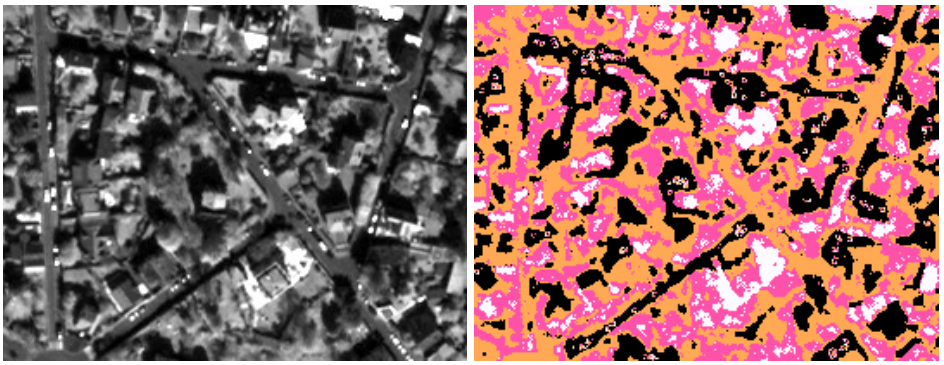


Figure 19.12: Result of applying the `otb::MarkovRandomFieldFilter` to an extract from a PAN Quickbird image for classification into four classes using the Fisher-distribution as likehood term. From left to right : original image, classification.

```
markovFilter->SetInput(reader->GetOutput());

typedef itk::RescaleIntensityImageFilter
    < LabelledImageType, LabelledImageType > RescaleType;
RescaleType::Pointer rescaleFilter = RescaleType::New();
rescaleFilter->SetOutputMinimum(0);
rescaleFilter->SetOutputMaximum(255);

rescaleFilter->SetInput( markovFilter->GetOutput() );

writer->SetInput( rescaleFilter->GetOutput() );
writer->Update();
```

We can now create an image file writer and save the image.

```
typedef otb::ImageFileWriter<RGBImageType> WriterRescaledType;

WriterRescaledType::Pointer writerRescaled = WriterRescaledType::New();

writerRescaled->SetFileName( outputRescaledImageFileName );
writerRescaled->SetInput( colormapper->GetOutput() );

writerRescaled->Update();
```

Figure 19.12 shows the output of the Markov Random Field classification into four classes using the Fisher-distribution as likelihood term.

The source code for this example can be found in the file `Examples/Markov/MarkovRegularizationExample.cxx`.

This example illustrates the use of the `otb::MarkovRandomFieldFilter.` to regularize a classifi-

Figure 19.13: Result of applying the `otb::MarkovRandomFieldFilter` to regularized the result of another classification. From left to right : original classification, regularized classification

cation obtained previously by another classifier. Here we will apply the regularization to the output of an SVM classifier presented in 19.3.4.

The reference image and the starting image are both going to be the original classification. Both regularization and fidelity energy are defined by Potts model.

The convergence of the Markov Random Field is done with a random sampler and a Metropolis model as in example 1. As you should get use to the general program structure to use the MRF framework, we are not going to repeat the entire example. However, remember you can find the full source code for this example in your OTB source directory.

To find the number of classes available in the original image we use the `itk::LabelStatisticsImageFilter` and more particularly the method `GetNumberOfLabels()`.

```
typedef itk::LabelStatisticsImageFilter
<LabelledImageType, LabelledImageType> LabelledStatType;
LabelledStatType::Pointer labelledStat = LabelledStatType::New();
labelledStat->SetInput(reader->GetOutput());
labelledStat->SetLabelInput(reader->GetOutput());
labelledStat->Update();

unsigned int nClass = labelledStat->GetNumberOfLabels();
```

Figure 19.13 shows the output of the Markov Random Field regularization on the classification output of another method.

19.3 Supervised classification

19.3.1 Generic machine learning framework

The OTB supervised classification is implemented as a generic Machine Learning framework, supporting several possible machine learning libraries as backends. As of now both libSVM (the machine learning library historically integrated in OTB) and the machine learning methods of OpenCV library ([14]) are available.

The current list of classifiers available through the same generic interface within the OTB is:

- **LibSVM**: Support Vector Machines classifier based on libSVM.
- **SVM**: Support Vector Machines classifier based on OpenCV, itself based on libSVM.
- **Bayes**: Normal Bayes classifier based on OpenCV.
- **Boost**: Boost classifier based on OpenCV.
- **DT**: Decision Tree classifier based on OpenCV.
- **RF**: Random Forests classifier based on the Random Trees in OpenCV.
- **GBT**: Gradient Boosted Tree classifier based on OpenCV.
- **KNN**: K-Nearest Neighbors classifier based on OpenCV.
- **ANN**: Artificial Neural Network classifier based on OpenCV.

19.3.2 An example of supervised classification method: Support Vector Machines

SVM general description

Kernel based learning methods in general and the Support Vector Machines (SVM) in particular, have been introduced in the last years in learning theory for classification and regression tasks, [132]. SVM have been successfully applied to text categorization, [73], and face recognition, [102]. Recently, they have been successfully used for the classification of hyperspectral remote-sensing images, [15].

Simply stated, the approach consists in searching for the separating surface between 2 classes by the determination of the subset of training samples which best describes the boundary between the 2 classes. These samples are called support vectors and completely define the classification system. In the case where the two classes are nonlinearly separable, the method uses a kernel expansion in order to make projections of the feature space onto higher dimensionality spaces where the separation of the classes becomes linear.

SVM mathematical formulation

This subsection reminds the basic principles of SVM learning and classification. A good tutorial on SVM can be found in, [17].

We have N samples represented by the couple $(y_i, \mathbf{x}_i), i = 1 \ldots N$ where $y_i \in \{-1, +1\}$ is the class label and $\mathbf{x}_i \in \mathbb{R}^n$ is the feature vector of dimension n. A classifier is a function

$$f(\mathbf{x}, \alpha) : \mathbf{x} \mapsto y$$

where α are the classifier parameters. The SVM finds the optimal separating hyperplane which fulfills the following constraints :

- The samples with labels $+1$ and -1 are on different sides of the hyperplane.
- The distance of the closest vectors to the hyperplane is maximised. These are the support vectors (SV) and this distance is called the margin.

The separating hyperplane has the equation

$$\mathbf{w} \cdot \mathbf{x} + b = 0;$$

with $\mathbf{w}$ being its normal vector and x being any point of the hyperplane. The orthogonal distance to the origin is given by $\frac{|b|}{\|\mathbf{w}\|}$. Vectors located outside the hyperplane have either $\mathbf{w} \cdot \mathbf{x} + b > 0$ or $\mathbf{w} \cdot \mathbf{x} + b < 0$.

Therefore, the classifier function can be written as

$$f(\mathbf{x}, \mathbf{w}, b) = sgn(\mathbf{w} \cdot \mathbf{x} + b).$$

The SVs are placed on two hyperplanes which are parallel to the optimal separating one. In order to find the optimal hyperplane, one sets $\mathbf{w}$ and b :

$$\mathbf{w} \cdot \mathbf{x} + b = \pm 1.$$

Since there must not be any vector inside the margin, the following constraint can be used:

$$\mathbf{w} \cdot \mathbf{x}_i + b \geq +1 \text{ if } y_i = +1;$$

$$\mathbf{w} \cdot \mathbf{x}_i + b \leq -1 \text{ if } y_i = -1;$$

which can be rewritten as

$$y_i(\mathbf{w} \cdot \mathbf{x}_i + b) - 1 \geq 0 \ \ \forall i.$$

The orthogonal distances of the 2 parallel hyperplanes to the origin are $\frac{|1-b|}{\|\mathbf{w}\|}$ and $\frac{|-1-b|}{\|\mathbf{w}\|}$. Therefore the modulus of the margin is equal to $\frac{2}{\|\mathbf{w}\|}$ and it has to be maximised.

Thus, the problem to be solved is:

- Find $\mathbf{w}$ and b which minimise $\left\{\frac{1}{2}\|\mathbf{w}\|^2\right\}$
- under the constraint : $y_i(\mathbf{w}\cdot\mathbf{x}_i+b)\geq 1 \;\; i=1\ldots N$.

This problem can be solved by using the Lagrange multipliers with one multiplier per sample. It can be shown that only the support vectors will have a positive Lagrange multiplier.

In the case where the two classes are not exactly linearly separable, one can modify the constraints above by using

$$\mathbf{w}\cdot\mathbf{x}_i+b\geq+1-\xi_i \text{ if } y_i=+1;$$
$$\mathbf{w}\cdot\mathbf{x}_i+b\leq-1+\xi_i \text{ if } y_i=-1;$$
$$\xi_i\geq 0 \;\; \forall i.$$

If $\xi_i>1$, one considers that the sample is wrong. The function which has then to be minimised is $\frac{1}{2}\|\mathbf{w}\|^2+C\left(\sum_i\xi_i\right)$;, where C is a tolerance parameter. The optimisation problem is the same than in the linear case, but one multiplier has to be added for each new constraint $\xi_i\geq 0$.

If the decision surface needs to be non-linear, this solution cannot be applied and the kernel approach has to be adopted.

One drawback of the SVM is that, in their basic version, they can only solve two-class problems. Some works exist in the field of multi-class SVM (see [4, 136], and the comparison made by [59]), but they are not used in our system.

You have to be aware that to achieve better convergence of the algorithm it is strongly advised to normalize feature vector components in the $[-1;1]$ interval.

For problems with $N>2$ classes, one can choose either to train N SVM (one class against all the others), or to train $N\times(N-1)$ SVM (one class against each of the others). In the second approach, which is the one that we use, the final decision is taken by choosing the class which is most often selected by the whole set of SVM.

19.3.3 Learning from samples

The source code for this example can be found in the file
`Examples/Learning/TrainMachineLearningModelFromSamplesExample.cxx`.

This example illustrates the use of the `otb::SVMMachineLearningModel` class, which inherits from the `otb::MachineLearningModel` class. This class allows the estimation of a classification model (supervised learning) from samples. In this example, we will train an SVM model with 4 output classes, from 1000 randomly generated training samples, each of them having 7 components. We start by including the appropriate header files.

```
// List sample generator
#include "otbListSampleGenerator.h"
```

```
// Random number generator
#include "itkMersenneTwisterRandomVariateGenerator.h"

// SVM model Estimator
#include "otbSVMMachineLearningModel.h"
```

The input parameters of the sample generator and of the SVM classifier are initialized.

```
  int nbSamples = 1000;
  int nbSampleComponents = 7;
  int nbClasses = 4;
```

Two lists are generated into a `itk::Statistics::ListSample` which is the structure used to handle both lists of samples and of labels for the machine learning classes derived from `otb::MachineLearningModel`. The first list is composed of feature vectors representing multi-component samples, and the second one is filled with their corresponding class labels. The list of labels is composed of scalar values.

```
  // Input related typedefs
  typedef float InputValueType;
  typedef itk::VariableLengthVector<InputValueType> InputSampleType;
  typedef itk::Statistics::ListSample<InputSampleType> InputListSampleType;

  // Target related typedefs
  typedef int TargetValueType;
  typedef itk::FixedArray<TargetValueType, 1> TargetSampleType;
  typedef itk::Statistics::ListSample<TargetSampleType> TargetListSampleType;

  InputListSampleType::Pointer InputListSample = InputListSampleType::New();
  TargetListSampleType::Pointer TargetListSample = TargetListSampleType::New();
```

In this example, the list of multi-component training samples is randomly filled with a random number generator based on the `itk::Statistics::MersenneTwisterRandomVariateGenerator` class. Each component's value is generated from a normal law centered around the corresponding class label of each sample multiplied by 100, with a standard deviation of 10.

```
  itk::Statistics::MersenneTwisterRandomVariateGenerator::Pointer randGen;
  randGen = itk::Statistics::MersenneTwisterRandomVariateGenerator::GetInstance();

  // Filling the two input training lists
  for (int i = 0; i < nbSamples; ++i)
    {
    InputSampleType sample;
    TargetValueType label = (i % nbClasses) + 1;

    // Multi-component sample randomly filled from a normal law for each component
    sample.SetSize(nbSampleComponents);
    for (int itComp = 0; itComp < nbSampleComponents; ++itComp)
      {
      sample[itComp] = randGen->GetNormalVariate(100 * label, 10);
      }

    InputListSample->PushBack(sample);
```

```
    TargetListSample->PushBack(label);
    }
```

Once both sample and label lists are generated, the second step consists in declaring the machine learning classifier. In our case we use an SVM model with the help of the `otb::SVMMachineLearningModel` class which is derived from the `otb::MachineLearningModel` class. This pure virtual class is based on the machine learning framework of the OpenCV library ([14]) which handles other classifiers than the SVM.

```
typedef otb::SVMMachineLearningModel<InputValueType, TargetValueType> SVMType;

SVMType::Pointer SVMClassifier = SVMType::New();

SVMClassifier->SetInputListSample(InputListSample);
SVMClassifier->SetTargetListSample(TargetListSample);

SVMClassifier->SetKernelType(CvSVM::LINEAR);
```

Once the classifier is parametrized with both input lists and default parameters, except for the kernel type in our example of SVM model estimation, the model training is computed with the `Train` method. Finally, the `Save` method exports the model to a text file. All the available classifiers based on OpenCV are implemented with these interfaces. Like for the SVM model training, the other classifiers can be parametrized with specific settings.

```
SVMClassifier->Train();
SVMClassifier->Save(outputModelFileName);
```

19.3.4 Learning from images

The source code for this example can be found in the file `Examples/Learning/TrainMachineLearningModelFromImagesExample.cxx`.

This example illustrates the use of the `otb::MachineLearningModel` class. This class allows the estimation of a classification model (supervised learning) from images. In this example, we will train an SVM with 4 classes. We start by including the appropriate header files.

```
// List sample generator
#include "otbListSampleGenerator.h"

// Extract a ROI of the vectordata
#include "otbVectorDataIntoImageProjectionFilter.h"

// SVM model Estimator
#include "otbSVMMachineLearningModel.h"
```

In this framework, we must transform the input samples store in a vector data into a `itk::Statistics::ListSample` which is the structure compatible with the machine learning classes. On the one hand, we are using feature vectors for the characterization of the classes,

and on the other hand, the class labels are scalar values. We first re-project the input vector data over the input image, using the `otb::VectorDataIntoImageProjectionFilter` class. To convert the input samples store in a vector data into a `itk::Statistics::ListSample`, we use the `otb::ListSampleGenerator` class.

```
// VectorData projection filter
typedef otb::VectorDataIntoImageProjectionFilter<VectorDataType, InputImageType>
                                                        VectorDataReprojectionType;

InputReaderType::Pointer inputReader = InputReaderType::New();
inputReader->SetFileName(inputImageFileName);

InputImageType::Pointer image = inputReader->GetOutput();
image->UpdateOutputInformation();

// Read the Vectordata
VectorDataReaderType::Pointer vectorReader = VectorDataReaderType::New();
vectorReader->SetFileName(trainingShpFileName);
vectorReader->Update();

VectorDataType::Pointer vectorData = vectorReader->GetOutput();
vectorData->Update();

VectorDataReprojectionType::Pointer vdreproj = VectorDataReprojectionType::New();

vdreproj->SetInputImage(image);
vdreproj->SetInput(vectorData);
vdreproj->SetUseOutputSpacingAndOriginFromImage(false);

vdreproj->Update();

typedef otb::ListSampleGenerator<InputImageType, VectorDataType>
                                                        ListSampleGeneratorType;
ListSampleGeneratorType::Pointer sampleGenerator;
sampleGenerator = ListSampleGeneratorType::New();

sampleGenerator->SetInput(image);
sampleGenerator->SetInputVectorData(vdreproj->GetOutput());
sampleGenerator->SetClassKey("Class");

sampleGenerator->Update();
```

Now, we need to declare the machine learning model which will be used by the classifier. In this example, we train an SVM model. The `otb::SVMMachineLearningModel` class inherits from the pure virtual class `otb::MachineLearningModel` which is templated over the type of values used for the measures and the type of pixels used for the labels. Most of the classification and regression algorithms available through this interface in OTB is based on the OpenCV library [14]. Specific methods can be used to set classifier parameters. In the case of SVM, we set here the type of the kernel. Other parameters are let with their default values.

```
typedef otb::SVMMachineLearningModel
                            <InputImageType::InternalPixelType,
```

```
                                    ListSampleGeneratorType::ClassLabelType> SVMType;

  SVMType::Pointer SVMClassifier = SVMType::New();

  SVMClassifier->SetInputListSample(sampleGenerator->GetTrainingListSample());
  SVMClassifier->SetTargetListSample(sampleGenerator->GetTrainingListLabel());

  SVMClassifier->SetKernelType(CvSVM::LINEAR);
```

The machine learning interface is generic and gives access to other classifiers. We now train the SVM model using the `Train` and save the model to a text file using the `Save` method.

```
  SVMClassifier->Train();
  SVMClassifier->Save(outputModelFileName);
```

You can now use the `Predict` method which takes a `itk::Statistics::ListSample` as input and estimates the label of each input sample using the model. Finally, the `otb::ImageClassificationModel` inherits from the `itk::ImageToImageFilter` and allows to classify pixels in the input image by predicting their labels using a model.

19.3.5 Multi-band, streamed classification

The source code for this example can be found in the file `Examples/Classification/SupervisedImageClassificationExample.cxx`.

In OTB, a generic streamed filter called `otb::ImageClassificationFilter` is available to classify any input multi-channel image according to an input classification model file. This filter is generic because it works with any classification model type (SVM, KNN, Artificial Neural Network,...) generated within the OTB generic Machine Learning framework based on OpenCV ([14]). The input model file is smartly parsed according to its content in order to identify which learning method was used to generate it. Once the classification method and model are known, the input image can be classified. More details are given in subsections 19.3.3 and 19.3.4 to generate a classification model either from samples or from images. In this example we will illustrate its use. We start by including the appropriate header files.

```
#include "otbMacro.h"
#include "otbMachineLearningModelFactory.h"
#include "otbImageClassificationFilter.h"
```

We will assume double precision input images and will also define the type for the labeled pixels.

```
  const unsigned int     Dimension = 2;
  typedef double         PixelType;
  typedef unsigned short LabeledPixelType;
```

Our classifier is generic enough to be able to process images with any number of bands. We read the input image as a `otb::VectorImage`. The labeled image will be a scalar image.

```
typedef otb::VectorImage<PixelType, Dimension>  ImageType;
typedef otb::Image<LabeledPixelType, Dimension> LabeledImageType;
```

We can now define the type for the classifier filter, which is templated over its input and output image types.

```
typedef otb::ImageClassificationFilter<ImageType, LabeledImageType>
                                                        ClassificationFilterType;
typedef ClassificationFilterType::ModelType ModelType;
```

Moreover, it is necessary to define a `otb::MachineLearningModelFactory` which is templated over its input and output pixel types. This factory is used to parse the input model file and to define which classification method to use.

```
typedef otb::MachineLearningModelFactory<PixelType, LabeledPixelType>
                                                    MachineLearningModelFactoryType;
```

And finally, we define the reader and the writer. Since the images to classify can be very big, we will use a streamed writer which will trigger the streaming ability of the classifier.

```
typedef otb::ImageFileReader<ImageType>        ReaderType;
typedef otb::ImageFileWriter<LabeledImageType> WriterType;
```

We instantiate the classifier and the reader objects and we set the existing model obtained in a previous training step.

```
ClassificationFilterType::Pointer filter = ClassificationFilterType::New();

ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(infname);
```

The input model file is parsed according to its content and the generated model is then loaded within the `otb::ImageClassificationFilter`.

```
ModelType::Pointer model;
model = MachineLearningModelFactoryType::CreateMachineLearningModel(
                                    modelfname,
                                    MachineLearningModelFactoryType::ReadMode);
model->Load(modelfname);

filter->SetModel(model);
```

We plug the pipeline and trigger its execution by updating the output of the writer.

```
filter->SetInput(reader->GetOutput());

WriterType::Pointer writer = WriterType::New();
writer->SetInput(filter->GetOutput());
writer->SetFileName(outfname);
writer->Update();
```

19.3.6 Generic Kernel SVM

OTB has developed a specific interface for user-defined kernels. However, the following functions use a deprecated OTB interface. A function $k(\cdot,\cdot)$ is considered to be a kernel when:

$$\forall g(\cdot) \in \mathcal{L}^2(\mathbb{R}^n) \quad \text{so that} \quad \int g(x)^2 dx \text{ be finite,} \qquad \text{then} \quad \int k(x,y)\, g(x)\, g(y)\, dxdy \geqslant 0, \tag{19.5}$$

which is known as the *Mercer condition*.

When defined through the OTB, a kernel is a class that inherits from `GenericKernelFunctorBase`. Several virtual functions have to be overloaded:

- The `Evaluate` function, which implements the behavior of the kernel itself. For instance, the classical linear kernel could be re-implemented with:

```
double
MyOwnNewKernel
::Evaluate ( const svm_node * x, const svm_node * y,
             const svm_parameter & param ) const
{
        return this->dot(x,y);
}
```

  This simple example shows that the classical dot product is already implemented into `otb::GenericKernelFunctorBase::dot()` as a protected function.

- The `Update()` function which synchronizes local variables and their integration into the initial SVM procedure. The following examples will show the way to use it.

Some pre-defined generic kernels have already been implemented in OTB:

- `otb::MixturePolyRBFKernelFunctor` which implements a linear mixture of a polynomial and a RBF kernel;
- `otb::NonGaussianRBFKernelFunctor` which implements a non gaussian RBF kernel;
- `otb::SpectralAngleKernelFunctor`, a kernel that integrates the Spectral Angle, instead of the Euclidean distance, into an inverse multiquadric kernel. This kernel may be appropriated when using multispectral data.
- `otb::ChangeProfileKernelFunctor`, a kernel which is dedicated to the supervized classification of the multiscale change profile presented in section 21.5.1.

Learning with User Defined Kernels

The source code for this example can be found in the file
`Examples/Learning/SVMGenericKernelImageModelEstimatorExample.cxx`.

This example illustrates the modifications to be added to the use of `otb::SVMImageModelEstimator` in order to add a user defined kernel. This initial program has been explained in section 19.3.4.

The first thing to do is to include the header file for the new kernel.

```
#include "otbSVMImageModelEstimator.h"
#include "otbMixturePolyRBFKernelFunctor.h"
```

Once the `otb::SVMImageModelEstimator` is instanciated, it is possible to add the new kernel and its parameters.

Then in addition to the initial code:

```
  EstimatorType::Pointer svmEstimator = EstimatorType::New();

  svmEstimator->SetSVMType(C_SVC);
  svmEstimator->SetInputImage(inputReader->GetOutput());
  svmEstimator->SetTrainingImage(trainingReader->GetOutput());
```

The instanciation of the kernel is to be implemented. The kernel which is used here is a linear combination of a polynomial kernel and an RBF one. It is written as

$$\mu k_1(x,y) + (1-\mu)k_2(x,y)$$

with $k_1(x,y) = (\gamma_1 x \cdot y + c_0)^d$ and $k_2(x,y) = \exp\left(-\gamma_2 \|x-y\|^2\right)$. Then, the specific parameters of this kernel are:

- `Mixture` (μ),
- `GammaPoly` (γ_1),
- `CoefPoly` (c_0),
- `DegreePoly` (d),
- `GammaRBF` (γ_2).

Their instanciations are achieved through the use of the `SetValue` function.

```
  otb::MixturePolyRBFKernelFunctor myKernel;
  myKernel.SetValue("Mixture", 0.5);
  myKernel.SetValue("GammaPoly", 1.0);
  myKernel.SetValue("CoefPoly", 0.0);
  myKernel.SetValue("DegreePoly", 1);
  myKernel.SetValue("GammaRBF", 1.5);
  myKernel.Update();
```

Once the kernel's parameters are affected and the kernel updated, the connection to `otb::SVMImageModelEstimator` takes place here.

```
svmEstimator->SetKernelFunctor(&myKernel);
svmEstimator->SetKernelType(GENERIC);
```

The model estimation procedure is triggered by calling the estimator's `Update` method.

```
svmEstimator->Update();
```

The rest of the code remains unchanged...

```
svmEstimator->SaveModel(outputModelFileName);
```

In the file `outputModelFileName` a specific line will appear when using a generic kernel. It gives the name of the kernel and its parameters name and value.

Classification with user defined kernel

The source code for this example can be found in the file `Examples/Learning/SVMGenericKernelImageClassificationExample.cxx`.

This example illustrates the modifications to be added to use the `otb::SVMClassifier` class for performing SVM classification on images with a user-defined kernel. In this example, we will use an SVM model estimated in the previous section to separate between water and non-water pixels by using the RGB values only. The first thing to do is include the header file for the class as well as the header of the appropriated kernel to be used.

```
#include "otbSVMClassifier.h"
#include "otbMixturePolyRBFKernelFunctor.h"
```

We need to declare the SVM model which is to be used by the classifier. The SVM model is templated over the type of value used for the measures and the type of pixel used for the labels.

```
typedef otb::SVMModel<PixelType, LabelPixelType> ModelType;
ModelType::Pointer model = ModelType::New();
```

After instantiation, we can load a model saved to a file (see section 19.3.4 for an example of model estimation and storage to a file).

When using a user defined kernel, an explicit instanciation has to be performed.

```
otb::MixturePolyRBFKernelFunctor myKernel;
model->SetKernelFunctor(&myKernel);
```

Then, the rest of the classification program remains unchanged.

```
model->LoadModel(modelFilename);
```

19.4 Fusion of Classification maps

19.4.1 General approach of image fusion

In order to obtain a relevant image classification it is sometimes necessary to fuse several classification maps coming from different classification methods (SVM, KNN, Random Forest, Artificial Neural Networks,...). The fusion of classification maps combines them in a more robust and precise one. Two methods are available in the OTB: the majority voting and the Demspter Shafer framework.

19.4.2 Majority voting

General description

For each input pixel, the Majority Voting method consists in choosing the more frequent class label among all classification maps to fuse. In case of not unique more frequent class labels, the undecided value is set for such pixels in the fused output image.

An example of majority voting fusion

The source code for this example can be found in the file `Examples/Classification/MajorityVotingFusionOfClassificationMapsExample.cxx`.

The Majority Voting fusion filter `itk::LabelVotingImageFilter` used is based on ITK. For each pixel, it chooses the more frequent class label among the input classification maps. In case of not unique more frequent class labels, the output pixel is set to the *undecidedLabel* value. We start by including the appropriate header file.

```
#include "itkLabelVotingImageFilter.h"
```

We will assume unsigned short type input labeled images.

```
const unsigned int     Dimension = 2;
typedef unsigned short LabelPixelType;
```

The input labeled images to be fused are expected to be scalar images.

```
typedef otb::Image<LabelPixelType, Dimension> LabelImageType;
```

The Majority Voting fusion filter `itk::LabelVotingImageFilter` based on ITK is templated over the input and output labeled image type.

```
// Majority Voting
typedef itk::LabelVotingImageFilter<LabelImageType, LabelImageType>
                                                    LabelVotingFilterType;
```

Both reader and writer are defined. Since the images to classify can be very big, we will use a streamed writer which will trigger the streaming ability of the fusion filter.

```
typedef otb::ImageFileReader<LabelImageType> ReaderType;
typedef otb::ImageFileWriter<LabelImageType> WriterType;
```

The input classification maps to be fused are pushed into the `itk::LabelVotingImageFilter`. Moreover, the label value for the undecided pixels (in case of not unique majority voting) is set too.

```
ReaderType::Pointer reader;
LabelVotingFilterType::Pointer labelVotingFilter = LabelVotingFilterType::New();
for (unsigned int itCM = 0; itCM < nbClassificationMaps; ++itCM)
  {
  std::string fileNameClassifiedImage = argv[itCM + 1];

  reader = ReaderType::New();
  reader->SetFileName(fileNameClassifiedImage);
  reader->Update();

  labelVotingFilter->SetInput(itCM, reader->GetOutput());
  }

labelVotingFilter->SetLabelForUndecidedPixels(undecidedLabel);
```

Once it is plugged the pipeline triggers its execution by updating the output of the writer.

```
WriterType::Pointer writer = WriterType::New();
writer->SetInput(labelVotingFilter->GetOutput());
writer->SetFileName(outfname);
writer->Update();
```

19.4.3 Dempster Shafer

General description

A more adaptive fusion method using the Dempster Shafer theory (http://en.wikipedia.org/wiki/Dempster-Shafer_theory) is available within the OTB. This method is adaptive as it is based on the so-called belief function of each class label for each classification map. Thus, each classified pixel is associated to a degree of confidence according to the classifier used. In the Dempster Shafer framework, the expert's point of view (i.e. with a high belief function) is considered as the truth. In order to estimate the belief function of each class label, we use the Dempster Shafer combination of masses of belief for each class label and for each classification map. In this framework, the output fused label of each pixel is the one with the maximal belief function.

Like for the majority voting method, the Dempster Shafer fusion handles not unique class labels with the maximal belief function. In this case, the output fused pixels are set to the undecided value.

The confidence levels of all the class labels are estimated from a comparision of the classification maps to fuse with a ground truth, which results in a confusion matrix. For each classification maps, these confusion matrices are then used to estimate the mass of belief of each class label.

Mathematical formulation of the combination algorithm

A description of the mathematical formulation of the Dempster Shafer combination algorithm is available in the following OTB Wiki page: http://wiki.orfeo-toolbox.org/index.php/Information_fusion_framework.

An example of Dempster Shafer fusion

The source code for this example can be found in the file `Examples/Classification/DempsterShaferFusionOfClassificationMapsExample.cxx`.

The fusion filter `otb::DSFusionOfClassifiersImageFilter` is based on the Dempster Shafer (DS) fusion framework. For each pixel, it chooses the class label *Ai* for which the belief function *bel(Ai)* is maximal after the DS combination of all the available masses of belief of all the class labels. The masses of belief (MOBs) of all the labels present in each classification map are read from input *.CSV confusion matrix files. Moreover, the pixels into the input classification maps to be fused which are equal to the *nodataLabel* value are ignored by the fusion process. In case of not unique class labels with the maximal belief function, the output pixels are set to the *undecidedLabel* value. We start by including the appropriate header files.

```
#include "otbImageListToVectorImageFilter.h"
#include "otbConfusionMatrixToMassOfBelief.h"
#include "otbDSFusionOfClassifiersImageFilter.h"

#include <fstream>
```

We will assume unsigned short type input labeled images. We define a type for confusion matrices as `itk::VariableSizeMatrix` which will be used to estimate the masses of belief of all the class labels for each input classification map. For this purpose, the `otb::ConfusionMatrixToMassOfBelief` will be used to convert each input confusion matrix into masses of belief for each class label.

```
  typedef unsigned short LabelPixelType;
  typedef unsigned long ConfusionMatrixEltType;
  typedef itk::VariableSizeMatrix<ConfusionMatrixEltType> ConfusionMatrixType;
  typedef otb::ConfusionMatrixToMassOfBelief
           <ConfusionMatrixType, LabelPixelType> ConfusionMatrixToMassOfBeliefType;
  typedef ConfusionMatrixToMassOfBeliefType::MapOfClassesType MapOfClassesType;
```

The input labeled images to be fused are expected to be scalar images.

```
  const unsigned int      Dimension = 2;
```

```
typedef otb::Image<LabelPixelType, Dimension> LabelImageType;
typedef otb::VectorImage<LabelPixelType, Dimension> VectorImageType;
```

We declare an otb::ImageListToVectorImageFilter which will stack all the input classification maps to be fused as a single VectorImage for which each band is a classification map. This VectorImage will then be the input of the Dempster Shafer fusion filter otb::DSFusionOfClassifiersImageFilter.

```
typedef otb::ImageList<LabelImageType> LabelImageListType;
typedef otb::ImageListToVectorImageFilter
          <LabelImageListType, VectorImageType> ImageListToVectorImageFilterType;
```

The Dempster Shafer fusion filter otb::DSFusionOfClassifiersImageFilter is declared.

```
// Dempster Shafer
typedef otb::DSFusionOfClassifiersImageFilter
      <VectorImageType, LabelImageType> DSFusionOfClassifiersImageFilterType;
```

Both reader and writer are defined. Since the images to classify can be very big, we will use a streamed writer which will trigger the streaming ability of the fusion filter.

```
typedef otb::ImageFileReader<LabelImageType> ReaderType;
typedef otb::ImageFileWriter<LabelImageType> WriterType;
```

The image list of input classification maps is filled. Moreover, the input confusion matrix files are converted into masses of belief.

```
ReaderType::Pointer reader;
LabelImageListType::Pointer imageList = LabelImageListType::New();
ConfusionMatrixToMassOfBeliefType::Pointer confusionMatrixToMassOfBeliefFilter;
confusionMatrixToMassOfBeliefFilter = ConfusionMatrixToMassOfBeliefType::New();

MassOfBeliefDefinitionMethod massOfBeliefDef;

// Several parameters are available to estimate the masses of belief
// from the confusion matrices: PRECISION, RECALL, ACCURACY and KAPPA
massOfBeliefDef = ConfusionMatrixToMassOfBeliefType::PRECISION;

VectorOfMapOfMassesOfBeliefType vectorOfMapOfMassesOfBelief;
for (unsigned int itCM = 0; itCM < nbClassificationMaps; ++itCM)
  {
  std::string fileNameClassifiedImage = argv[itCM + 1];
  std::string fileNameConfMat = argv[itCM + 1 + nbClassificationMaps];

  reader = ReaderType::New();
  reader->SetFileName(fileNameClassifiedImage);
  reader->Update();

  imageList->PushBack(reader->GetOutput());

  MapOfClassesType mapOfClassesClk;
  ConfusionMatrixType confusionMatrixClk;
```

```
  // The data (class labels and confusion matrix values) are read and
  // extracted from the *.CSV file with an ad-hoc file parser
  CSVConfusionMatrixFileReader(
      fileNameConfMat, mapOfClassesClk, confusionMatrixClk);

  // The parameters of the ConfusionMatrixToMassOfBelief filter are set
  confusionMatrixToMassOfBeliefFilter->SetMapOfClasses(mapOfClassesClk);
  confusionMatrixToMassOfBeliefFilter->SetConfusionMatrix(confusionMatrixClk);
  confusionMatrixToMassOfBeliefFilter->SetDefinitionMethod(massOfBeliefDef);
  confusionMatrixToMassOfBeliefFilter->Update();

  // Vector containing ALL the K (= nbClassificationMaps) std::map<Label, MOB>
  // of Masses of Belief
  vectorOfMapOfMassesOfBelief.push_back(
      confusionMatrixToMassOfBeliefFilter->GetMapMassOfBelief());
  }
```

The image list of input classification maps is converted into a VectorImage to be used as input of the `otb::DSFusionOfClassifiersImageFilter`.

```
// Image List To VectorImage
ImageListToVectorImageFilterType::Pointer imageListToVectorImageFilter;
imageListToVectorImageFilter = ImageListToVectorImageFilterType::New();
imageListToVectorImageFilter->SetInput(imageList);

DSFusionOfClassifiersImageFilterType::Pointer dsFusionFilter;
dsFusionFilter = DSFusionOfClassifiersImageFilterType::New();

// The parameters of the DSFusionOfClassifiersImageFilter are set
dsFusionFilter->SetInput(imageListToVectorImageFilter->GetOutput());
dsFusionFilter->SetInputMapsOfMassesOfBelief(&vectorOfMapOfMassesOfBelief);
dsFusionFilter->SetLabelForNoDataPixels(nodataLabel);
dsFusionFilter->SetLabelForUndecidedPixels(undecidedLabel);
```

Once it is plugged the pipeline triggers its execution by updating the output of the writer.

```
WriterType::Pointer writer = WriterType::New();
writer->SetInput(dsFusionFilter->GetOutput());
writer->SetFileName(outfname);
writer->Update();
```

19.5 Classification map regularization

The source code for this example can be found in the file `Examples/Classification/ClassificationMapRegularizationExample.cxx`.

After having generated a classification map, it is possible to regularize such a labeled image in order to obtain more homogeneous areas, which makes the interpretation of its classes easier. For

this purpose, the otb::NeighborhoodMajorityVotingImageFilter was implemented. Like a morphological filter, this filter uses majority voting in a ball shaped neighborhood in order to set each pixel of the classification map to the more representative label value in its neighborhood.

In this example we will illustrate its use. We start by including the appropriate header file.

```
#include "otbNeighborhoodMajorityVotingImageFilter.h"
```

Since the input image is a classification map, we will assume a single band input image for which each pixel value is a label coded on 8 bits as an integer between 0 and 255.

```
typedef unsigned char IOLabelPixelType; // 8 bits
const unsigned int Dimension = 2;
```

Thus, both input and output images are single band labeled images, which are composed of the same type of pixels in this example (unsigned char).

```
typedef otb::Image<IOLabelPixelType, Dimension> IOLabelImageType;
```

We can now define the type for the neighborhood majority voting filter, which is templated over its input and output images types and over its structuring element type. Choosing only the input image type in the template of this filter induces that, both input and output images types are the same and that the structuring element is a ball (itk::BinaryBallStructuringElement).

```
// Neighborhood majority voting filter type
typedef otb::NeighborhoodMajorityVotingImageFilter<IOLabelImageType>
 NeighborhoodMajorityVotingFilterType;
```

Since the otb::NeighborhoodMajorityVotingImageFilter is a neighborhood based image filter, it is necessary to set the structuring element which will be used for the majority voting process. By default, the structuring element is a ball (itk::BinaryBallStructuringElement) with a radius defined by two sizes (respectively along X and Y). Thus, it is possible to handle anisotropic structuring elements such as ovals.

```
// Binary ball Structuring Element type
typedef NeighborhoodMajorityVotingFilterType::KernelType StructuringType;
typedef StructuringType::RadiusType RadiusType;
```

Finally, we define the reader and the writer.

```
typedef otb::ImageFileReader<IOLabelImageType> ReaderType;
typedef otb::ImageFileWriter<IOLabelImageType> WriterType;
```

We instantiate the otb::NeighborhoodMajorityVotingImageFilter and the reader objects.

```
// Neighborhood majority voting filter
NeighborhoodMajorityVotingFilterType::Pointer NeighMajVotingFilter;
NeighMajVotingFilter = NeighborhoodMajorityVotingFilterType::New();

ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(inputFileName);
```

The ball shaped structuring element seBall is instantiated and its two radii along X and Y are initialized.

```
StructuringType seBall;
RadiusType rad;

rad[0] = radiusX;
rad[1] = radiusY;

seBall.SetRadius(rad);
seBall.CreateStructuringElement();
```

Then, this ball shaped neighborhood is used as the kernel structuring element for the `otb::NeighborhoodMajorityVotingImageFilter`.

```
NeighMajVotingFilter->SetKernel(seBall);
```

Not classified input pixels are assumed to have the noDataValue label and will keep this label in the output image.

```
NeighMajVotingFilter->SetLabelForNoDataPixels(noDataValue);
```

Moreover, since the majority voting regularization may lead to not unique majority labels in the neighborhood, it is important to define which behaviour the filter must have in this case. For this purpose, a Boolean parameter is used in the filter to choose whether pixels with more than one majority class are set to undecidedValue (true), or to their Original labels (false = default value) in the output image.

```
NeighMajVotingFilter->SetLabelForUndecidedPixels(undecidedValue);

if (KeepOriginalLabelBoolStr.compare("true") == 0)
{
  NeighMajVotingFilter->SetKeepOriginalLabelBool(true);
}
else
{
  NeighMajVotingFilter->SetKeepOriginalLabelBool(false);
}
```

We plug the pipeline and trigger its execution by updating the output of the writer.

```
NeighMajVotingFilter->SetInput(reader->GetOutput());

WriterType::Pointer writer = WriterType::New();
writer->SetFileName(outputFileName);
writer->SetInput(NeighMajVotingFilter->GetOutput());
writer->Update();
```

CHAPTER

TWENTY

OBJECT-BASED IMAGE ANALYSIS

Object-Based Image Analysis (OBIA) focusses on analyzing images at the object level instead of working at the pixel level. This approach is particularly well adapted for high resolution images and leads to more robust and less noisy results.

OTB allows to implement OBIA by using ITK's Label Object framework (`http://www.insight-journal.org/browse/publication/176`). This allows to represent a segmented image as a set of regions and not anymore as a set of pixels. Added to the compression rate achieved by this kind of description, the main advantage of this approach is the possibility to operate at the segment (or object level).

A classical OBIA pipeline will use the following steps:

1. Image segmentation (the whole or only parts of it);
2. Image to LabelObjectMap (a kind of `std::map<LabelObject>`) transformation;
3. Eventual relabeling;
4. Attribute computation for the regions using the image before segmentation:
   (a) Shape attributes;
   (b) Statistics attributes;
   (c) Attributes for radiometry, textures, etc.
5. Object filtering
   (a) Remove/select objects under a condition (area less than X, NDVI higher than X, etc.)
   (b) Keep N objects;
   (c) etc.
6. LabelObjectMap to image transformation.

20.1 From Images to Objects

The source code for this example can be found in the file
`Examples/OBIA/ImageToLabelToImage.cxx`.

This example shows the basic approach for the transformation of a segmented (labeled) image into a LabelObjectMap and then back to an image. For this matter we will need the following header files which contain the basic classes.

```
#include "itkLabelObject.h"
#include "itkLabelMap.h"
#include "itkBinaryImageToLabelMapFilter.h"
#include "itkLabelMapToLabelImageFilter.h"
```

The image types are defined using pixel types and dimension. The input image is defined as an `otb::Image`.

```
  const int dim                              = 2;
  typedef unsigned short              PixelType;
  typedef otb::Image<PixelType, dim> ImageType;

  typedef itk::LabelObject<PixelType, dim> LabelObjectType;
  typedef itk::LabelMap<LabelObjectType>   LabelMapType;
```

As usual, the reader is instantiated and the input image is set.

```
  typedef otb::ImageFileReader<ImageType> ReaderType;
  ReaderType::Pointer reader = ReaderType::New();
  reader->SetFileName(argv[1]);
```

Then the binary image is transformed to a collection of label objects. Arguments are:

- `FullyConnected`: Set whether the connected components are defined strictly by face connectivity or by face+edge+vertex connectivity. Default is FullyConnectedOff.
- `InputForegroundValue/OutputBackgroundValue`: Specify the pixel value of input/output of the foreground/background.

```
  typedef itk::BinaryImageToLabelMapFilter<ImageType, LabelMapType> I2LType;
  I2LType::Pointer i2l = I2LType::New();
  i2l->SetInput(reader->GetOutput());
  i2l->SetFullyConnected(atoi(argv[5]));
  i2l->SetInputForegroundValue(atoi(argv[6]));
  i2l->SetOutputBackgroundValue(atoi(argv[7]));
```

Then the inverse process is used to recreate a image of labels. The `itk::LabelMapToLabelImageFilter` converts a LabelMap to a labeled image.

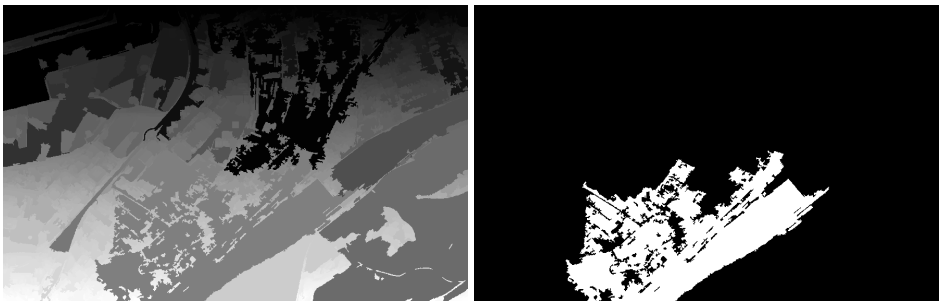


Figure 20.1: Transforming an image (left) into a label object map and back to an image (right).

```
typedef itk::LabelMapToLabelImageFilter<LabelMapType, ImageType> L2IType;
L2IType::Pointer l2i = L2IType::New();
l2i->SetInput(i2l->GetOutput());
```

The output can be passed to a writer. The invocation of the `Update()` method on the writer triggers the execution of the pipeline.

```
typedef otb::ImageFileWriter<ImageType> WriterType;
WriterType::Pointer writer = WriterType::New();
writer->SetInput(l2i->GetOutput());
writer->SetFileName(argv[2]);
writer->Update();
```

Figure 20.1 shows the effect of transforming an image into a label object map and back to an image

20.2 Object Attributes

The source code for this example can be found in the file
`Examples/OBIA/ShapeAttributeComputation.cxx`.

This basic example shows how compute shape attributes at the object level. The input image is firstly converted into a set of regions (`itk::ShapeLabelObject`), some attribute values of each object are computed and then saved to an ASCII file.

```
#include "itkShapeLabelObject.h"
#include "itkLabelMap.h"
#include "itkLabelImageToLabelMapFilter.h"
#include "itkShapeLabelMapFilter.h"
```

The image types are defined using pixel types and dimensions. The input image is defined as an `otb::Image`.

```
const int dim = 2;
typedef unsigned long                          PixelType;
typedef otb::Image<PixelType, dim>             ImageType;
typedef unsigned long                          LabelType;
typedef itk::ShapeLabelObject<LabelType, dim> LabelObjectType;
typedef itk::LabelMap<LabelObjectType>         LabelMapType;
typedef itk::LabelImageToLabelMapFilter
<ImageType, LabelMapType> ConverterType;
```

Firstly, the image reader is instantiated.

```
typedef otb::ImageFileReader<ImageType> ReaderType;
ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(argv[1]);
```

Here the `itk::ShapeLabelObject` type is chosen in order to read some attributes related to the shape of the objects, by opposition to the content of the object, with the `itk::StatisticsLabelObject`.

```
typedef itk::ShapeLabelMapFilter<LabelMapType> ShapeFilterType;
```

The input image is converted in a collection of objects

```
ConverterType::Pointer converter = ConverterType::New();
converter->SetInput(reader->GetOutput());
converter->SetBackgroundValue(itk::NumericTraits<LabelType>::min());

ShapeFilterType::Pointer shape = ShapeFilterType::New();

shape->SetInput(converter->GetOutput());
```

Update the shape filter, so its output will be up to date.

```
shape->Update();
```

Then, we can read the attribute values we're interested in. The `itk::BinaryImageToShapeLabelMapFilter` produces consecutive labels, so we can use a for loop and `GetLabelObject()` method to retrieve the label objects. If the labels are not consecutive, the `GetNthLabelObject()` method must be use instead of `GetLabelObject()`, or an iterator on the label object container of the label map. In this example, we write 2 shape attributes of each object to a text file (the size and the centroid coordinates).

```
std::ofstream outfile(argv[2]);

LabelMapType::Pointer labelMap = shape->GetOutput();
for (unsigned long label = 1;
     label <= labelMap->GetNumberOfLabelObjects();
     label++)
  {
  // We don't need a SmartPointer of the label object here,
```

```
    // because the reference is kept in the label map.
    const LabelObjectType * labelObject = labelMap->GetLabelObject(label);
    outfile << label << "\t" << labelObject->GetPhysicalSize() << "\t"
            << labelObject->GetCentroid() << std::endl;
    }

  outfile.close();
```

20.3 Object Filtering based on radiometric and statistics attributes

The source code for this example can be found in the file `Examples/OBIA/RadiometricAttributesLabelMapFilterExample.cxx`.

This example shows the basic approach to perform object based analysis on a image. The input image is firstly segmented using the `otb::MeanShiftImageFilter` Then each segmented region is converted to a Map of labeled objects. Afterwards the `otb::otbMultiChannelRAndNIRIndexImageFilter` computes radiometric attributes for each object. In this example the NDVI is computed. The computed feature is passed to the `otb::BandsStatisticsAttributesLabelMapFilter` which computes statistics over the resulting band. Therefore, region's statistics over each band can be access by concatening STATS, the band number and the statistical attribute separated by colons. In this example the mean of the first band (which contains the NDVI) is access over all the regions with the attribute: 'STATS::Band1::Mean'.

Firstly, segment the input image by using the Mean Shift algorithm (see 8.7.2 for deeper explanations).

```
  typedef otb::MeanShiftVectorImageFilter
  <VectorImageType, VectorImageType, LabeledImageType> FilterType;
  FilterType::Pointer filter = FilterType::New();
  filter->SetSpatialRadius(spatialRadius);
  filter->SetRangeRadius(rangeRadius);
  filter->SetMinimumRegionSize(minRegionSize);
  filter->SetScale(scale);
```

The `otb::MeanShiftImageFilter` type is instantiated using the image types.

```
  filter->SetInput(vreader->GetOutput());
```

The `itk::LabelImageToLabelMapFilter` type is instantiated using the output of the `otb::MeanShiftImageFilter`. This filter produces a labeled image where each segmented region has a unique label.

```
  LabelMapFilterType::Pointer labelMapFilter = LabelMapFilterType::New();
  labelMapFilter->SetInput(filter->GetLabeledClusteredOutput());
  labelMapFilter->SetBackgroundValue(itk::NumericTraits<LabelType>::min());
```

```
ShapeLabelMapFilterType::Pointer shapeLabelMapFilter =
  ShapeLabelMapFilterType::New();
shapeLabelMapFilter->SetInput(labelMapFilter->GetOutput());
```

Instantiate the `otb::RadiometricLabelMapFilterType` to compute statistics of the feature image on each label object.

```
RadiometricLabelMapFilterType::Pointer radiometricLabelMapFilter
  = RadiometricLabelMapFilterType::New();
```

Feature image could be one of the following image:

- GEMI
- NDVI
- IR
- IC
- IB
- NDWI2
- Intensity

Input image must be convert to the desired coefficient. In our case, statistics are computed on the NDVI coefficient on each label object.

```
NDVIImageFilterType:: Pointer ndviImageFilter = NDVIImageFilterType::New();

ndviImageFilter->SetRedIndex(3);
ndviImageFilter->SetNIRIndex(4);
ndviImageFilter->SetInput(vreader->GetOutput());

ImageToVectorImageCastFilterType::Pointer ndviVectorImageFilter =
    ImageToVectorImageCastFilterType::New();

ndviVectorImageFilter->SetInput(ndviImageFilter->GetOutput());

radiometricLabelMapFilter->SetInput(shapeLabelMapFilter->GetOutput());
radiometricLabelMapFilter->SetFeatureImage(ndviVectorImageFilter->GetOutput());
```

The `otb::AttributesMapOpeningLabelMapFilter` will perform the selection. There are three parameters. `AttributeName` specifies the radiometric attribute, `Lambda` controls the thresholding of the input and `ReverseOrdering` make this filter to remove the object with an attribute value greater than `Lambda` instead.

```
OpeningLabelMapFilterType::Pointer opening = OpeningLabelMapFilterType::New();
opening->SetInput(radiometricLabelMapFilter->GetOutput());
opening->SetAttributeName(attr);
opening->SetLambda(thresh);
opening->SetReverseOrdering(lowerThan);
opening->Update();
```

Then, Label objects selected are transform in a Label Image using the `itk::LabelMapToLabelImageFilter`.

```
LabelMapToBinaryImageFilterType::Pointer labelMap2LabeledImage
  = LabelMapToBinaryImageFilterType::New();
labelMap2LabeledImage->SetInput(opening->GetOutput());
```

And finally, we declare the writer and call its `Update()` method to trigger the full pipeline execution.

```
WriterType::Pointer writer = WriterType::New();

writer->SetFileName(outfname);
writer->SetInput(labelMap2LabeledImage->GetOutput());
writer->Update();
```

Figure 20.2 shows the result of applying the object selection based on radiometric attributes.

Figure 20.2: Vegetation mask resulting from processing.

20.4 Hoover metrics to compare segmentations

The source code for this example can be found in the file
`Examples/OBIA/HooverMetricsEstimation.cxx`.

The following example shows how to compare two segmentations, using Hoover metrics. For instance, it can be used to compare a segmentation produced by your algorithm against a partial ground truth segmentation. In this example, the ground truth segmentation will be refered by the letters GT whereas the machine segmentation will be refered by MS.

The estimation of Hoover metrics is done with two filters : `otb::HooverMatrixFilter` and `otb::HooverInstanceFilter`. The first one produces a matrix containing the number of overlapping pixels between MS regions and GT regions. The second one classifies each region among four types (called Hoover instances):

- Correct detection : a region is matched with an other one in the opposite segmentation, because they cover nearly the same area.
- Over-segmentation : a GT region is matched with a group of MS regions because they cover nearly the same area.
- Under-segmentation : a MS region is matched with a group of GT regions because they cover nearly the same area.
- Missed detection (for GT regions) or Noise (for MS region) : un-matched regions.

Note that a region can be tagged with two types. When the Hoover instance have been found, the instance filter computes overall scores for each category : they are the Hoover metrics [1].

```
#include "otbHooverMatrixFilter.h"
#include "otbHooverInstanceFilter.h"
#include "otbLabelMapToAttributeImageFilter.h"
```

The filters `otb::HooverMatrixFilter` and `otb::HooverInstanceFilter` are designed to handle `itk::LabelMap` images, made with `otb::AttributesMapLabelObject`. This type of label object allows to store generic attributes. Each region can store a set of attributes: in this case, Hoover instances and metrics will be stored.

```
  typedef otb::AttributesMapLabelObject<unsigned int, 2, float> LabelObjectType;
  typedef itk::LabelMap<LabelObjectType>            LabelMapType;
  typedef otb::HooverMatrixFilter<LabelMapType>     HooverMatrixFilterType;
  typedef otb::HooverInstanceFilter<LabelMapType>   InstanceFilterType;

  typedef otb::Image<unsigned int, 2>               ImageType;
  typedef itk::LabelImageToLabelMapFilter
    <ImageType, LabelMapType>                       ImageToLabelMapFilterType;
```

[1] see http://www.trop.mips.uha.fr/pdf/ORASIS-2009.pdf

```
typedef otb::VectorImage<float, 2>                VectorImageType;
typedef otb::LabelMapToAttributeImageFilter
    <LabelMapType, VectorImageType>               AttributeImageFilterType;
```

The first step is to convert the images to label maps : we use `itk::LabelImageToLabelMapFilter`. The background value sets the label value of regions considered as background: there is no label object for the background region.

```
ImageToLabelMapFilterType::Pointer gt_filter = ImageToLabelMapFilterType::New();
gt_filter->SetInput(gt_reader->GetOutput());
gt_filter->SetBackgroundValue(0);

ImageToLabelMapFilterType::Pointer ms_filter = ImageToLabelMapFilterType::New();
ms_filter->SetInput(ms_reader->GetOutput());
ms_filter->SetBackgroundValue(0);
```

The Hoover matrix filter has to be updated here. This matrix must be computed before being given to the instance filter.

```
HooverMatrixFilterType::Pointer hooverFilter = HooverMatrixFilterType::New();
hooverFilter->SetGroundTruthLabelMap(gt_filter->GetOutput());
hooverFilter->SetMachineSegmentationLabelMap(ms_filter->GetOutput());
hooverFilter->Update();
```

The instance filter computes the Hoover metrics for each region. These metrics are stored as attributes in each label object. The threshold parameter corresponds to the overlapping ratio above which two regions can be matched. The extended attributes can be used if the user wants to keep a trace of the associations between MS and GT regions : i.e. if a GT region has been matched as a correct detection, it will carry an attribute containing the label value of the associated MS region (the same principle goes for other types of instance).

```
InstanceFilterType::Pointer instances = InstanceFilterType::New();
instances->SetGroundTruthLabelMap(gt_filter->GetOutput());
instances->SetMachineSegmentationLabelMap(ms_filter->GetOutput());
instances->SetThreshold(0.75);
instances->SetHooverMatrix(hooverFilter->GetHooverConfusionMatrix());
instances->SetUseExtendedAttributes(false);
```

The `otb::LabelMapToAttributeImageFilter` is designed to extract attributes values from a label map and output them in the channels of a vector image. We set the attribute to plot in each channel.

```
AttributeImageFilterType::Pointer attributeImageGT = AttributeImageFilterType::New();
attributeImageGT->SetInput(instances->GetOutputGroundTruthLabelMap());
attributeImageGT->SetAttributeForNthChannel(0, InstanceFilterType::GetNameFromAttribute(Inst
attributeImageGT->SetAttributeForNthChannel(1, InstanceFilterType::GetNameFromAttribute(Inst
attributeImageGT->SetAttributeForNthChannel(2, InstanceFilterType::GetNameFromAttribute(Inst
attributeImageGT->SetAttributeForNthChannel(3, InstanceFilterType::GetNameFromAttribute(Inst

WriterType::Pointer writer = WriterType::New();
writer->SetInput(attributeImageGT->GetOutput());
writer->SetFileName(argv[3]);
```

```
writer->Update();
```

The output image contains for each GT region its correct detection score (”RC”, band 1), its over-segmentation score (”RF”, band 2), its under-segmentation score (”RA”, band 3) and its missed detection score (”RM”, band 4).

```
std::cout << "Mean RC ="<< instances->GetMeanRC() << std::endl;
std::cout << "Mean RF ="<< instances->GetMeanRF() << std::endl;
std::cout << "Mean RA ="<< instances->GetMeanRA() << std::endl;
std::cout << "Mean RM ="<< instances->GetMeanRM() << std::endl;
std::cout << "Mean RN ="<< instances->GetMeanRN() << std::endl;
```

The Hoover scores are also computed for the whole segmentations. Here is some explanation about the score names : C = correct, F = fragmentation, A = aggregation, M = missed, N = noise.

CHAPTER

TWENTYONE

CHANGE DETECTION

21.1 Introduction

Change detection techniques try to detect and locate areas which have changed between two or more observations of the same scene. These changes can be of different types, with different origins and of different temporal length. This allows to distinguish different kinds of applications:

- *land use monitoring*, which corresponds to the characterization of the evolution of the vegetation, or its seasonal changes;
- *natural resources management*, which corresponds mainly to the characterization of the evolution of the urban areas, the evolution of the deforestation, etc.
- *damage mapping*, which corresponds to the location of damages caused by natural or industrial disasters.

From the point of view of the observed phenomena, one can distinguish 2 types of changes whose nature is rather different: the abrupt changes and the progressive changes, which can eventually be periodic. From the data point of view, one can have:

- Image pairs before and after the event. The applications are mainly the abrupt changes.
- Multi-temporal image series on which 2 types on changes may appear:
  - The slow changes like for instance the erosion, vegetation evolution, etc. The knowledge of the studied phenomena and of their consequences on the geometrical and radiometrical evolution at the different dates is a very important information for this kind of analysis.
  - The abrupt changes may pose different kinds of problems depending on whether the date of the change is known in the image series or not. The detection of areas affected by a change occurred at a known date may exploit this a priori information in order to split

the image series into two sub-series (before an after) and use the temporal redundancy in order to improve the detection results. On the other hand, when the date of the change is not known, the problem has a higher difficulty.

From this classification of the different types of problems, one can infer 4 cases for which one can look for algorithms as a function of the available data:

1. Abrupt changes in an image pair. This is no doubt the field for which more work has been done. One can find tools at the 3 classical levels of image processing: data level (differences, ratios, with or without pre-filtering, etc.), feature level (edges, targets, etc.), and interpretation level (post-classification comparison).
2. Abrupt changes within an image series and a known date. One can rely on bi-date techniques, either by fusing the images into 2 stacks (before and after), or by fusing the results obtained by different image couples (one after and one before the event). One can also use specific discontinuity detection techniques to be applied in the temporal axis.
3. Abrupt changes within an image series and an unknown date. This case can be seen either as a generalization of the preceding one (testing the N-1 positions for N dates) or as a particular case of the following one.
4. Progressive changes within an image series. One can work in two steps:
   (a) detect the change areas using stability criteria in the temporal areas;
   (b) identify the changes using prior information about the type of changes of interest.

21.1.1 Surface-based approaches

In this section we discuss about the damage assessment techniques which can be applied when only two images (before/after) are available.

As it has been shown in recent review works [30, 89, 113, 115], a relatively high number of methods exist, but most of them have been developed for optical and infrared sensors. Only a few recent works on change detection with radar images exist [126, 16, 101, 68, 38, 11, 70]. However, the intrinsic limits of passive sensors, mainly related to their dependence on meteorological and illumination conditions, impose severe constraints for operational applications. The principal difficulties related to change detection are of four types:

1. In the case of radar images, the speckle noise makes the image exploitation difficult.
2. The geometric configuration of the image acquisition can produce images which are difficult to compare.

3. Also, the temporal gap between the two acquisitions and thus the sensor aging and the inter-calibration are sources of variability which are difficult to deal with.

4. Finally, the normal evolution of the observed scenes must not be confused with the changes of interest.

The problem of detecting abrupt changes between a pair of images is the following: Let I_1, I_2 be two images acquired at different dates t_1, t_2; we aim at producing a thematic map which shows the areas where changes have taken place.

Three main categories of methods exist:

- Strategy 1: Post Classification Comparison

  The principle of this approach [34] is two obtain two land-use maps independently for each date and comparing them.

- Strategy 2: Joint classification

  This method consists in producing the change map directly from a joint classification of both images.

- Strategy 3: Simple detectors

  The last approach consists in producing an image of change likelihood (by differences, ratios or any other approach) and thresholding it in order to produce the change map.

Because of its simplicity and its low computation overhead, the third strategy is the one which has been chosen for the processing presented here.

21.2 Change Detection Framework

The source code for this example can be found in the file
`Examples/ChangeDetection/ChangeDetectionFrameworkExample.cxx`.

This example illustrates the Change Detector framework implemented in OTB. This framework uses the generic programming approach. All change detection filters are `otb::BinaryFunctorNeighborhoodImageFilter`s, that is, they are filters taking two images as input and providing one image as output. The change detection computation itself is performed on a the neighborhood of each pixel of the input images.

The first step required to build a change detection filter is to include the header of the parent class.

```
#include "otbBinaryFunctorNeighborhoodImageFilter.h"
```

The change detection operation itself is one of the templates of the change detection filters and takes the form of a function, that is, something accepting the syntax `foo()`. This can be implemented using classical C/C++ functions, but it is preferable to implement it using C++ functors. These are classical C++ classes which overload the `()` operator. This allows to use them with the same syntax as C/C++ functions.

Since change detectors operate on neighborhoods, the functor call will take 2 arguments which are `itk::ConstNeighborhoodIterator`s.

The change detector functor is templated over the types of the input iterators and the output result type. The core of the change detection is implemented in the `operator()` section.

```
template<class TInput1, class TInput2, class TOutput>
class MyChangeDetector
{
public:
  // The constructor and destructor.
  MyChangeDetector() {}
  ~MyChangeDetector() {}
  // Change detection operation
  inline TOutput operator ()(const TInput1& itA,
                             const TInput2& itB)
  {

    TOutput result = 0.0;

    for (unsigned long pos = 0; pos < itA.Size(); ++pos)
      {

      result += static_cast<TOutput>(itA.GetPixel(pos) - itB.GetPixel(pos));

      }
    return static_cast<TOutput>(result / itA.Size());
  }
};
```

The interest of using functors is that complex operations can be performed using internal `protected` class methods and that class variables can be used to store information so different pixel locations can access to results of previous computations.

The next step is the definition of the change detector filter. As stated above, this filter will inherit from `otb::BinaryFunctorNeighborhoodImageFilter` which is templated over the 2 input image types, the output image type and the functor used to perform the change detection operation.

Inside the class only a few `typedef`s and the constructors and destructors have to be declared.

```
template <class TInputImage1, class TInputImage2, class TOutputImage>
class ITK_EXPORT MyChangeDetectorImageFilter :
  public otb::BinaryFunctorNeighborhoodImageFilter<
      TInputImage1, TInputImage2, TOutputImage,
      MyChangeDetector<
          typename itk::ConstNeighborhoodIterator<TInputImage1>,
          typename itk::ConstNeighborhoodIterator<TInputImage2>,
```

```
          typename TOutputImage::PixelType> >
{
public:
  /** Standard class typedefs. */
  typedef MyChangeDetectorImageFilter Self;

  typedef typename otb::BinaryFunctorNeighborhoodImageFilter<
      TInputImage1, TInputImage2, TOutputImage,
      MyChangeDetector<
          typename itk::ConstNeighborhoodIterator<TInputImage1>,
          typename itk::ConstNeighborhoodIterator<TInputImage2>,
          typename TOutputImage::PixelType>
      >  Superclass;

  typedef itk::SmartPointer<Self>       Pointer;
  typedef itk::SmartPointer<const Self> ConstPointer;

  /** Method for creation through the object factory. */
  itkNewMacro(Self);

protected:
  MyChangeDetectorImageFilter() {}
  virtual ~MyChangeDetectorImageFilter() {}

private:
  MyChangeDetectorImageFilter(const Self &); //purposely not implemented
  void operator =(const Self&); //purposely not implemented

};
```

Pay attention to the fact that no `.txx` file is needed, since filtering operation is implemented in the `otb::BinaryFunctorNeighborhoodImageFilter` class. So all the algorithmics part is inside the functor.

We can now write a program using the change detector.

As usual, we start by defining the image types. The internal computations will be performed with floating point precision, while the output image will be stored using one byte per pixel.

```
  typedef float                                    InternalPixelType;
  typedef unsigned char                            OutputPixelType;
  typedef otb::Image<InternalPixelType, Dimension> InputImageType1;
  typedef otb::Image<InternalPixelType, Dimension> InputImageType2;
  typedef otb::Image<InternalPixelType, Dimension> ChangeImageType;
  typedef otb::Image<OutputPixelType, Dimension>   OutputImageType;
```

We declare the readers, the writer, but also the `itk::RescaleIntensityImageFilter` which will be used to rescale the result before writing it to a file.

```
  typedef otb::ImageFileReader<InputImageType1> ReaderType1;
  typedef otb::ImageFileReader<InputImageType2> ReaderType2;
  typedef otb::ImageFileWriter<OutputImageType> WriterType;
  typedef itk::RescaleIntensityImageFilter<ChangeImageType,
```

```
    OutputImageType> RescalerType;
```

The next step is declaring the filter for the change detection.

```
typedef MyChangeDetectorImageFilter<InputImageType1, InputImageType2,
    ChangeImageType>      FilterType;
```

We connect the pipeline.

```
reader1->SetFileName(inputFilename1);
reader2->SetFileName(inputFilename2);
writer->SetFileName(outputFilename);
rescaler->SetOutputMinimum(itk::NumericTraits<OutputPixelType>::min());
rescaler->SetOutputMaximum(itk::NumericTraits<OutputPixelType>::max());

filter->SetInput1(reader1->GetOutput());
filter->SetInput2(reader2->GetOutput());
filter->SetRadius(atoi(argv[3]));

rescaler->SetInput(filter->GetOutput());
writer->SetInput(rescaler->GetOutput());
```

And that is all.

21.3 Simple Detectors

21.3.1 Mean Difference

The simplest change detector is based on the pixel-wise differencing of image values:

$$I_D(i,j) = I_2(i,j) - I_1(i,j). \tag{21.1}$$

In order to make the algorithm robust to noise, one actually uses local means instead of pixel values.

The source code for this example can be found in the file
`Examples/ChangeDetection/DiffChDet.cxx`.

This example illustrates the class `otb::MeanDifferenceImageFilter` for detecting changes between pairs of images. This filter computes the mean intensity in the neighborhood of each pixel of the pair of images to be compared and uses the difference of means as a change indicator. This example will use the images shown in figure 21.1. These correspond to the near infrared band of two Spot acquisitions before and during a flood.

We start by including the corresponding header file.

```
#include "otbMeanDifferenceImageFilter.h"
```

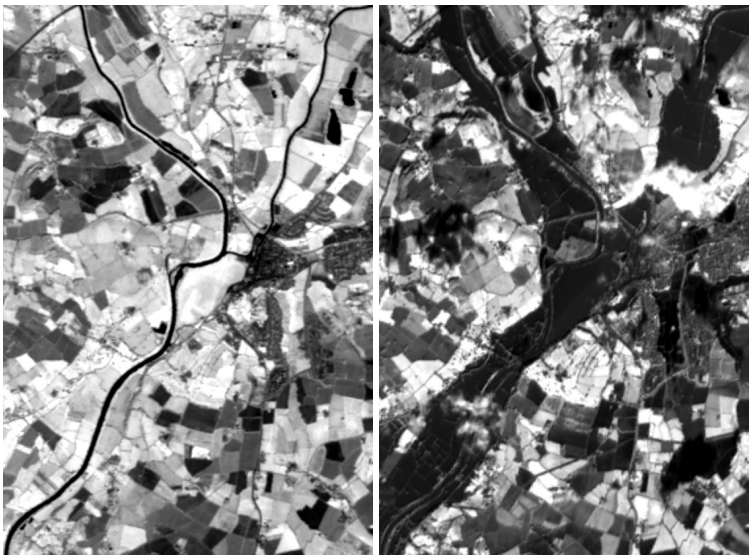


Figure 21.1: Images used for the change detection. Left: Before the flood. Right: during the flood.

We start by declaring the types for the two input images, the change image and the image to be stored in a file for visualization.

```
typedef float                                        InternalPixelType;
typedef unsigned char                                OutputPixelType;
typedef otb::Image<InternalPixelType, Dimension> InputImageType1;
typedef otb::Image<InternalPixelType, Dimension> InputImageType2;
typedef otb::Image<InternalPixelType, Dimension> ChangeImageType;
typedef otb::Image<OutputPixelType, Dimension>   OutputImageType;
```

We can now declare the types for the readers and the writer.

```
typedef otb::ImageFileReader<InputImageType1> ReaderType1;
typedef otb::ImageFileReader<InputImageType2> ReaderType2;
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

The change detector will give positive and negative values depending on the sign of the difference. We are usually interested only in the asbolute value of the difference. For this purpose, we will use the `itk::AbsImageFilter`. Also, before saving the image to a file in, for instance, PNG format, we will rescale the results of the change detection in order to use all the output pixel type range of values.

```
typedef itk::AbsImageFilter<ChangeImageType,
    ChangeImageType> AbsType;
typedef itk::RescaleIntensityImageFilter<ChangeImageType,
    OutputImageType> RescalerType;
```

The `otb::MeanDifferenceImageFilter` is templated over the types of the two input images and the type of the generated change image.

```
typedef otb::MeanDifferenceImageFilter<
    InputImageType1,
    InputImageType2,
    ChangeImageType>       FilterType;
```

The different elements of the pipeline can now be instantiated.

```
ReaderType1::Pointer  reader1 = ReaderType1::New();
ReaderType2::Pointer  reader2 = ReaderType2::New();
WriterType::Pointer   writer = WriterType::New();
FilterType::Pointer   filter = FilterType::New();
AbsType::Pointer      absFilter = AbsType::New();
RescalerType::Pointer rescaler = RescalerType::New();
```

We set the parameters of the different elements of the pipeline.

```
reader1->SetFileName(inputFilename1);
reader2->SetFileName(inputFilename2);
writer->SetFileName(outputFilename);
rescaler->SetOutputMinimum(itk::NumericTraits<OutputPixelType>::min());
rescaler->SetOutputMaximum(itk::NumericTraits<OutputPixelType>::max());
```

The only parameter for this change detector is the radius of the window used for computing the mean of the intensities.

```
filter->SetRadius(atoi(argv[4]));
```

We build the pipeline by plugging all the elements together.

```
filter->SetInput1(reader1->GetOutput());
filter->SetInput2(reader2->GetOutput());
absFilter->SetInput(filter->GetOutput());
rescaler->SetInput(absFilter->GetOutput());
writer->SetInput(rescaler->GetOutput());
```

Since the processing time of large images can be long, it is interesting to monitor the evolution of the computation. In order to do so, the change detectors can use the command/observer design pattern. This is easily done by attaching an observer to the filter.

```
typedef otb::CommandProgressUpdate<FilterType> CommandType;

CommandType::Pointer observer = CommandType::New();
filter->AddObserver(itk::ProgressEvent(), observer);
```

Figure 21.2 shows the result of the change detection by difference of local means.

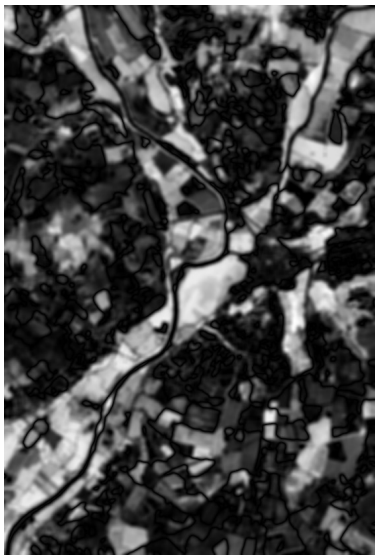


Figure 21.2: Result of the mean difference change detector

21.3.2 Ratio Of Means

This detector is similar to the previous one except that it uses a ratio instead of the difference:

$$I_R(i,j) = \frac{I_2(i,j)}{I_1(i,j)}. \tag{21.2}$$

The use of the ratio makes this detector robust to multiplicative noise which is a good model for the speckle phenomenon which is present in radar images.

In order to have a bounded and normalized detector the following expression is actually used:

$$I_R(i,j) = 1 - min\left(\frac{I_2(i,j)}{I_1(i,j)}, \frac{I_1(i,j)}{I_2(i,j)}\right). \tag{21.3}$$

The source code for this example can be found in the file
`Examples/ChangeDetection/RatioChDet.cxx`.

This example illustrates the class `otb::MeanRatioImageFilter` for detecting changes between pairs of images. This filter computes the mean intensity in the neighborhood of each pixel of the pair of images to be compared and uses the ratio of means as a change indicator. This change indicator is then normalized between 0 and 1 by using the classical

$$r = 1 - min\{\frac{\mu_A}{\mu_B}, \frac{\mu_B}{\mu_A}\}, \tag{21.4}$$

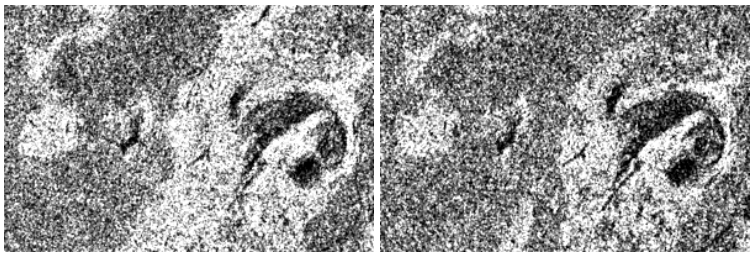


Figure 21.3: Images used for the change detection. Left: Before the eruption. Right: after the eruption.

where μ_A and μ_B are the local means. This example will use the images shown in figure 21.3. These correspond to 2 Radarsat fine mode acquisitions before and after a lava flow resulting from a volcanic eruption.

We start by including the corresponding header file.

```
#include "otbMeanRatioImageFilter.h"
```

We start by declaring the types for the two input images, the change image and the image to be stored in a file for visualization.

```
typedef float                                        InternalPixelType;
typedef unsigned char                                OutputPixelType;
typedef otb::Image<InternalPixelType, Dimension> InputImageType1;
typedef otb::Image<InternalPixelType, Dimension> InputImageType2;
typedef otb::Image<InternalPixelType, Dimension> ChangeImageType;
typedef otb::Image<OutputPixelType, Dimension>   OutputImageType;
```

We can now declare the types for the readers. Since the images can be vey large, we will force the pipeline to use streaming. For this purpose, the file writer will be streamed. This is achieved by using the `otb::ImageFileWriter` class.

```
typedef otb::ImageFileReader<InputImageType1>          ReaderType1;
typedef otb::ImageFileReader<InputImageType2>          ReaderType2;
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

The change detector will give a normalized result between 0 and 1. In order to store the result in PNG format we will rescale the results of the change detection in order to use all the output pixel type range of values.

```
typedef itk::ShiftScaleImageFilter<ChangeImageType,
    OutputImageType> RescalerType;
```

The `otb::MeanRatioImageFilter` is templated over the types of the two input images and the type of the generated change image.

```
typedef otb::MeanRatioImageFilter<
```

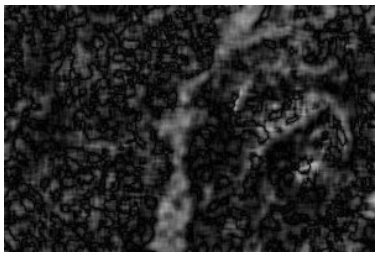


Figure 21.4: Result of the ratio of means change detector

```
    InputImageType1,
    InputImageType2,
    ChangeImageType>       FilterType;
```

The different elements of the pipeline can now be instantiated.

```
ReaderType1::Pointer  reader1 = ReaderType1::New();
ReaderType2::Pointer  reader2 = ReaderType2::New();
WriterType::Pointer   writer = WriterType::New();
FilterType::Pointer   filter = FilterType::New();
RescalerType::Pointer rescaler = RescalerType::New();
```

We set the parameters of the different elements of the pipeline.

```
reader1->SetFileName(inputFilename1);
reader2->SetFileName(inputFilename2);
writer->SetFileName(outputFilename);
float scale = itk::NumericTraits<OutputPixelType>::max();
rescaler->SetScale(scale);
```

The only parameter for this change detector is the radius of the window used for computing the mean of the intensities.

```
filter->SetRadius(atoi(argv[4]));
```

We build the pipeline by plugging all the elements together.

```
filter->SetInput1(reader1->GetOutput());
filter->SetInput2(reader2->GetOutput());

rescaler->SetInput(filter->GetOutput());
writer->SetInput(rescaler->GetOutput());
```

Figure 21.4 shows the result of the change detection by ratio of local means.

21.4 Statistical Detectors

21.4.1 Distance between local distributions

This detector is similar to the ratio of means detector (seen in the previous section page 517). Nevertheless, instead of the comparison of means, the comparison is performed to the complete distribution of the two Random Variables (RVs) [68].

The detector is based on the Kullback-Leibler distance between probability density functions (pdfs). In the neighborhood of each pixel of the pair of images I_1 and I_2 to be compared, the distance between local pdfs f_1 and f_2 of RVs X_1 and X_2 is evaluated by:

$$\mathcal{K}(X_1,X_2) = K(X_1|X_2) + K(X_2|X_1) \tag{21.5}$$

$$\text{with} \qquad K(X_j|X_i) = \int_{\mathbb{R}} \log \frac{f_{X_i}(x)}{f_{X_j}(x)} f_{X_i}(x)dx, \qquad i,j = 1,2. \tag{21.6}$$

In order to reduce the computational time, the local pdfs f_1 and f_2 are not estimated through histogram computations but rather by a cumulant expansion, namely the Edgeworth expansion, with is based on the cumulants of the RVs:

$$f_X(x) = \left(1 + \frac{\kappa_{X;3}}{6}H_3(x) + \frac{\kappa_{X;4}}{24}H_4(x) + \frac{\kappa_{X;5}}{120}H_5(x) + \frac{\kappa_{X;6} + 10\kappa_{X;3}^2}{720}H_6(x)\right)\mathcal{G}_X(x). \tag{21.7}$$

In eq. (21.7), $\mathcal{G}_X$ stands for the Gaussian pdf which has the same mean and variance as the RV X. The $\kappa_{X;k}$ coefficients are the cumulants of order k, and $H_k(x)$ are the Chebyshev-Hermite polynomials of order k (see [70] for deeper explanations).

The source code for this example can be found in the file
`Examples/ChangeDetection/KullbackLeiblerDistanceChDet.cxx`.

This example illustrates the class `otb::KullbackLeiblerDistanceImageFilter` for detecting changes between pairs of images. This filter computes the Kullback-Leibler distance between probability density functions (pdfs). In fact, the Kullback-Leibler distance is itself approximated through a cumulant-based expansion, since the pdfs are approximated through an Edgeworth series. The Kullback-Leibler distance is evaluated by:

$$\begin{aligned} K_{\text{Edgeworth}}(X_1|X_2) = {} & \frac{1}{12}\frac{\kappa_{X_1;3}^2}{\kappa_{X_1;2}^2} + \frac{1}{2}\left(\log\frac{\kappa_{X_2;2}}{\kappa_{X_1;2}} - 1 + \frac{1}{\kappa_{X_2;2}}\left(\kappa_{X_1;1} - \kappa_{X_2;1} + \kappa_{X_1;2}^{1/2}\right)^2\right) \\ & - \left(\kappa_{X_2;3}\frac{a_1}{6} + \kappa_{X_2;4}\frac{a_2}{24} + \kappa_{X_2;3}^2\frac{a_3}{72}\right) - \frac{1}{2}\frac{\kappa_{X_2;3}^2}{36}\left(c_6 - 6\frac{c_4}{\kappa_{X_1;2}} + 9\frac{c_2}{\kappa_{X_2;2}^2}\right) \\ & - 10\frac{\kappa_{X_1;3}\kappa_{X_2;3}\left(\kappa_{X_1;1} - \kappa_{X_2;1}\right)\left(\kappa_{X_1;2} - \kappa_{X_2;2}\right)}{\kappa_{X_2;2}^6} \end{aligned} \tag{21.8}$$

where

$$
\begin{aligned}
a_1 &= c_3 - 3\frac{\alpha}{\kappa_{X_2;2}} \\
a_2 &= c_4 - 6\frac{c_2}{\kappa_{X_2;2}} + \frac{3}{\kappa^2_{X_2;2}} \\
a_3 &= c_6 - 15\frac{c_4}{\kappa_{X_2;2}} + 45\frac{c_2}{\kappa^2_{X_2;2}} - \frac{15}{\kappa^3_{X_2;2}} \\
c_2 &= \alpha^2 + \beta^2 \\
c_3 &= \alpha^3 + 3\alpha\beta^2 \\
c_4 &= \alpha^4 + 6\alpha^2\beta^2 + 3\beta^4 \\
c_6 &= \alpha^6 + 15\alpha^4\beta^2 + 45\alpha^2\beta^4 + 15\beta^6 \\
\alpha &= \frac{\kappa_{X_1;1} - \kappa_{X_2;1}}{\kappa_{X_2;2}} \\
\beta &= \frac{\kappa^{1/2}_{X_1;2}}{\kappa_{X_2;2}}.
\end{aligned}
$$

$\kappa_{X_i;1}$, $\kappa_{X_i;2}$, $\kappa_{X_i;3}$ and $\kappa_{X_i;4}$ are the cumulants up to order 4 of the random variable X_i $(i = 1,2)$. This example will use the images shown in figure 21.3. These correspond to 2 Radarsat fine mode acquisitions before and after a lava flow resulting from a volcanic eruption.

The program itself is very similar to the ratio of means detector, implemented in `otb::MeanRatioImageFilter`, in section 21.3.2. Nevertheless the corresponding header file has to be used instead.

```
#include "otbKullbackLeiblerDistanceImageFilter.h"
```

The `otb::KullbackLeiblerDistanceImageFilter` is templated over the types of the two input images and the type of the generated change image, in a similar way as the `otb::MeanRatioImageFilter`. It is the only line to be changed from the ratio of means change detection example to perform a change detection through a distance between distributions...

```
    typedef otb::KullbackLeiblerDistanceImageFilter<ImageType,
        ImageType,
        ImageType> FilterType;
```

The different elements of the pipeline can now be instantiated. Follow the ratio of means change detector example.

The only parameter for this change detector is the radius of the window used for computing the cumulants.

```
    FilterType::Pointer filter = FilterType::New();
    filter->SetRadius((winSize - 1) / 2);
```

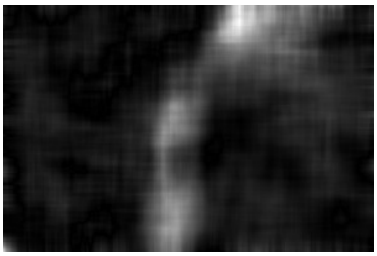


Figure 21.5: Result of the Kullback-Leibler change detector

The pipeline is built by plugging all the elements together.

```
filter->SetInput1(reader1->GetOutput());
filter->SetInput2(reader2->GetOutput());
```

Figure 21.5 shows the result of the change detection by computing the Kullback-Leibler distance between local pdf through an Edgeworth approximation.

21.4.2 Local Correlation

The correlation coefficient measures the likelihood of a linear relationship between two random variables:

$$\begin{aligned} I_\rho(i,j) &= \frac{1}{N}\frac{\sum_{i,j}(I_1(i,j)-m_{I_1})(I_2(i,j)-m_{I_2})}{\sigma_{I_1}\sigma_{I_2}} \\ &= \sum_{(I_1(i,j),I_2(i,j))}\frac{(I_1(i,j)-m_{I_1})(I_2(i,j)-m_{I_2})}{\sigma_{I_1}\sigma_{I_2}}p_{ij} \end{aligned} \tag{21.9}$$

where $I_1(i,j)$ and $I_2(i,j)$ are the pixel values of the 2 images and p_{ij} is the joint probability density. This is like using a linear model:

$$I_2(i,j) = (I_1(i,j)-m_{I_1})\frac{\sigma_{I_2}}{\sigma_{I_1}} + m_{I_2} \tag{21.10}$$

for which we evaluate the likelihood with p_{ij}.

With respect to the difference detector, this one will be robust to illumination changes.

The source code for this example can be found in the file
`Examples/ChangeDetection/CorrelChDet.cxx`.

This example illustrates the class `otb::CorrelationChangeDetector` for detecting changes between pairs of images. This filter computes the correlation coefficient in the neighborhood of each

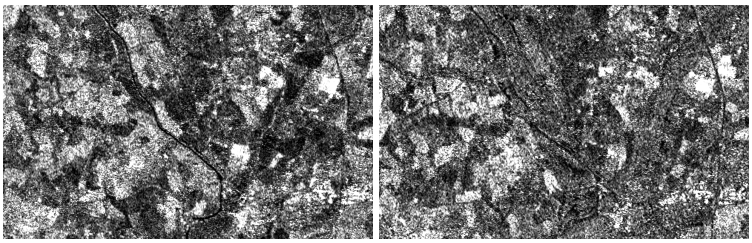


Figure 21.6: Images used for the change detection. Left: Before the flood. Right: during the flood.

pixel of the pair of images to be compared. This example will use the images shown in figure 21.6. These correspond to two ERS acquisitions before and during a flood.

We start by including the corresponding header file.

```
#include "otbCorrelationChangeDetector.h"
```

We start by declaring the types for the two input images, the change image and the image to be stored in a file for visualization.

```
typedef float                                       InternalPixelType;
typedef unsigned char                               OutputPixelType;
typedef otb::Image<InternalPixelType, Dimension> InputImageType1;
typedef otb::Image<InternalPixelType, Dimension> InputImageType2;
typedef otb::Image<InternalPixelType, Dimension> ChangeImageType;
typedef otb::Image<OutputPixelType, Dimension>   OutputImageType;
```

We can now declare the types for the readers. Since the images can be vey large, we will force the pipeline to use streaming. For this purpose, the file writer will be streamed. This is achieved by using the `otb::ImageFileWriter` class.

```
typedef otb::ImageFileReader<InputImageType1>          ReaderType1;
typedef otb::ImageFileReader<InputImageType2>          ReaderType2;
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

The change detector will give a response which is normalized between 0 and 1. Before saving the image to a file in, for instance, PNG format, we will rescale the results of the change detection in order to use all the output pixel type range of values.

```
typedef itk::ShiftScaleImageFilter<ChangeImageType,
    OutputImageType> RescalerType;
```

The `otb::CorrelationChangeDetector` is templated over the types of the two input images and the type of the generated change image.

```
typedef otb::CorrelationChangeDetector<
    InputImageType1,
```

```
    InputImageType2,
    ChangeImageType>       FilterType;
```

The different elements of the pipeline can now be instantiated.

```
ReaderType1::Pointer  reader1 = ReaderType1::New();
ReaderType2::Pointer  reader2 = ReaderType2::New();
WriterType::Pointer   writer = WriterType::New();
FilterType::Pointer   filter = FilterType::New();
RescalerType::Pointer rescaler = RescalerType::New();
```

We set the parameters of the different elements of the pipeline.

```
reader1->SetFileName(inputFilename1);
reader2->SetFileName(inputFilename2);
writer->SetFileName(outputFilename);

float scale = itk::NumericTraits<OutputPixelType>::max();
rescaler->SetScale(scale);
```

The only parameter for this change detector is the radius of the window used for computing the correlation coefficient.

```
filter->SetRadius(atoi(argv[4]));
```

We build the pipeline by plugging all the elements together.

```
filter->SetInput1(reader1->GetOutput());
filter->SetInput2(reader2->GetOutput());
rescaler->SetInput(filter->GetOutput());
writer->SetInput(rescaler->GetOutput());
```

Since the processing time of large images can be long, it is interesting to monitor the evolution of the computation. In order to do so, the change detectors can use the command/observer design pattern. This is easily done by attaching an observer to the filter.

```
typedef otb::CommandProgressUpdate<FilterType> CommandType;

CommandType::Pointer observer = CommandType::New();
filter->AddObserver(itk::ProgressEvent(), observer);
```

Figure 21.7 shows the result of the change detection by local correlation.

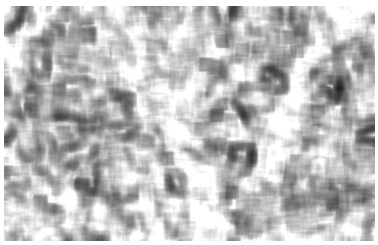


Figure 21.7: Result of the correlation change detector

21.5 Multi-Scale Detectors

21.5.1 Kullback-Leibler Distance between distributions

This technique is an extension of the distance between distributions change detector presented in section 21.4.1. Since this kind of detector is based on cumulants estimations through a sliding window, the idea is just to upgrade the estimation of the cumulants by considering new samples as soon as the sliding window is increasing in size.

Let's consider the following problem: how to update the moments when a $N+1^{th}$ observation x_{N+1} is added to a set of observations $\{x_1, x_2, \ldots, x_N\}$ already considered. The evolution of the central moments may be characterized by:

$$\begin{aligned} \mu_{1,[N]} &= \frac{1}{N} s_{1,[N]} \\ \mu_{r,[N]} &= \frac{1}{N} \sum_{\ell=0}^{r} \binom{r}{\ell} \left(-\mu_{1,[N]}\right)^{r-\ell} s_{\ell,[N]}, \end{aligned} \tag{21.11}$$

where the notation $s_{r,[N]} = \sum_{i=1}^{N} x_i^r$ has been used. Then, Edgeworth series is updated also by transforming moments to cumulants by using:

$$\begin{aligned} \kappa_{X;1} &= \mu_{X;1} \\ \kappa_{X;2} &= \mu_{X;2} - \mu_{X;1}^2 \\ \kappa_{X;3} &= \mu_{X;3} - 3\mu_{X;2}\mu_{X;1} + 2\mu_{X;1}^3 \\ \kappa_{X;4} &= \mu_{X;4} - 4\mu_{X;3}\mu_{X;1} - 3\mu_{X;2}^2 + 12\mu_{X;2}\mu_{X;1}^2 - 6\mu_{X;1}^4. \end{aligned} \tag{21.12}$$

It yields a set of images that represent the change measure according to an increasing size of the analysis window.

The source code for this example can be found in the file
`Examples/ChangeDetection/KullbackLeiblerProfileChDet.cxx`.

This example illustrates the class `otb::KullbackLeiblerProfileImageFilter` for detecting changes between pairs of images, according to a range of window size. This example is very similar,

in its principle, to all of the change detection examples, especially the distance between distributions one (section 21.4.1) which uses a fixed window size.

The main differences are:

1. a set of window range instead of a fixed size of window;
2. an output of type `otb::VectorImage`.

Then, the program begins with the `otb::VectorImage` and the `otb::KullbackLeiblerProfileImageFilter` header files in addition to those already details in the `otb::MeanRatioImageFilter` example.

```
#include "otbVectorImage.h"
#include "otbKullbackLeiblerProfileImageFilter.h"
```

The `otb::KullbackLeiblerProfileImageFilter` is templated over the types of the two input images and the type of the generated change image (which is now of multi-components), in a similar way as the `otb::KullbackLeiblerDistanceImageFilter`.

```
    typedef otb::Image<PixelType, Dimension>       ImageType;
    typedef otb::VectorImage<PixelType, Dimension> VectorImageType;
    typedef otb::KullbackLeiblerProfileImageFilter<ImageType,
        ImageType,
        VectorImageType> FilterType;
```

The different elements of the pipeline can now be instantiated in the same way as the ratio of means change detector example.

Two parameters are now required to give the minimum and the maximum size of the analysis window. The program will begin by performing change detection through the smaller window size and then applying moments update of eq. (21.11) by incrementing the radius of the analysis window (i.e. add a ring of width 1 pixel around the current neightborhood shape). The process is applied until the larger window size is reached.

```
    FilterType::Pointer filter = FilterType::New();
    filter->SetRadius((winSizeMin - 1) / 2, (winSizeMax - 1) / 2);
    filter->SetInput1(reader1->GetOutput());
    filter->SetInput2(reader2->GetOutput());
```

Figure 21.8 shows the result of the change detection by computing the Kullback-Leibler distance between local pdf through an Edgeworth approximation.

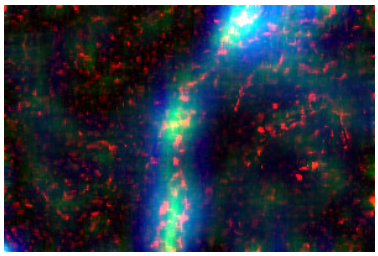


Figure 21.8: Result of the Kullback-Leibler profile change detector, colored composition including the first, 12th and 24th channel of the generated output.

21.6 Multi-components detectors

21.6.1 Multivariate Alteration Detector

The source code for this example can be found in the file
`Examples/ChangeDetection/MultivariateAlterationDetector.cxx`.

This example illustrates the class `otb::MultivariateAlterationChangeDetectorImageFilter`, which implements the Multivariate Alteration Change Detector algorithm [99]. This algorihtm allows to perform change detection from a pair multi-band images, including images with different number of bands or modalities. Its output is a a multi-band image of change maps, each one being unccorrelated with the remaining. The number of bands of the output image is the minimum number of bands between the two input images.

The algorithm works as follows. It tries to find two linear combinations of bands (one for each input images) which maximize correlation, and subtract these two linear combinitation, leading to the first change map. Then, it looks for a second set of linear combinations which are orthogonal to the first ones, a which maximize correlation, and use it as the second change map. This process is iterated until no more orthogonal linear combinations can be found.

This algorithms has numerous advantages, such as radiometry scaling and shifting invariance and absence of parameters, but it can not be used on a pair of single band images (in this case the output is simply the difference between the two images).

We start by including the corresponding header file.

```
#include "otbMultivariateAlterationDetectorImageFilter.h"
```

We then define the types for the input images and for the change image.

```
typedef unsigned short                                  InputPixelType;
typedef float                                           OutputPixelType;
typedef otb::VectorImage<InputPixelType, Dimension>  InputImageType;
typedef otb::VectorImage<OutputPixelType, Dimension> OutputImageType;
```

We can now declare the types for the reader. Since the images can be vey large, we will force the pipeline to use streaming. For this purpose, the file writer will be streamed. This is achieved by using the `otb::ImageFileWriter` class.

```
typedef otb::ImageFileReader<InputImageType>           ReaderType;
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

```
typedef otb::MultivariateAlterationDetectorImageFilter<
    InputImageType,OutputImageType>                    MADFilterType;
```

The different elements of the pipeline can now be instantiated.

```
ReaderType::Pointer    reader1 = ReaderType::New();
ReaderType::Pointer    reader2 = ReaderType::New();
WriterType::Pointer    writer = WriterType::New();
MADFilterType::Pointer madFilter = MADFilterType::New();
```

We set the parameters of the different elements of the pipeline.

```
reader1->SetFileName(inputFilename1);
reader2->SetFileName(inputFilename2);
writer->SetFileName(outputFilename);
```

We build the pipeline by plugging all the elements together.

```
madFilter->SetInput1(reader1->GetOutput());
madFilter->SetInput2(reader2->GetOutput());
writer->SetInput(madFilter->GetOutput());
```

And then we can trigger the pipeline update, as usual.

```
  writer->Update();
```

Figure 21.9 shows the results of Multivariate Alteration Detector applied to a pair of SPOT5 images before and after a flooding event.

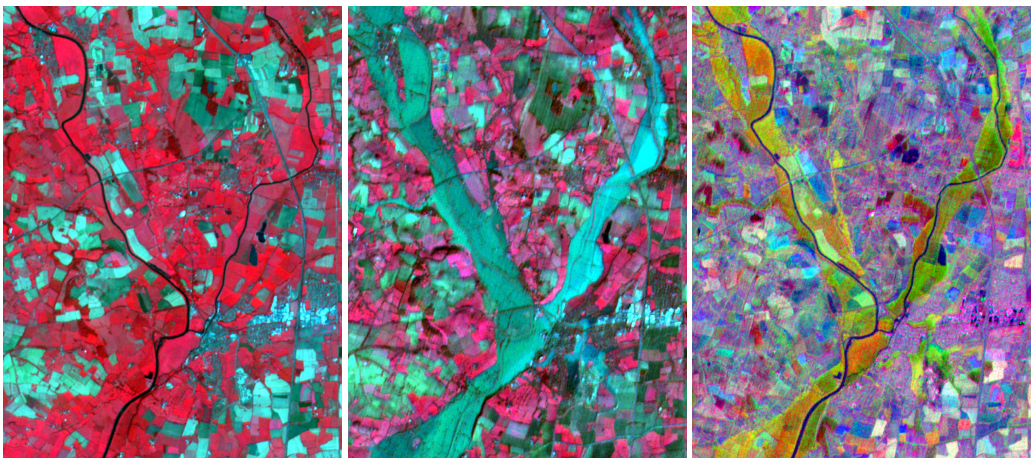


Figure 21.9: Result of the Multivariate Alteration Detector results on SPOT5 data before and after flooding.

CHAPTER

TWENTYTWO

HYPERSPECTRAL

An hyperspectral image contains a collection of spectral pixels or equivalently, a collection of spectral bands.

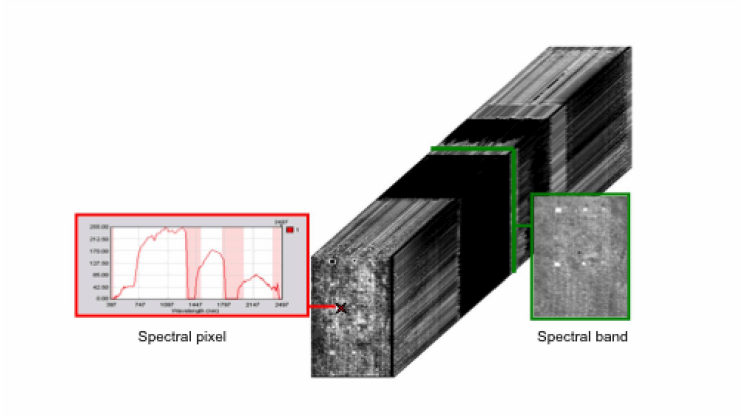


Figure 22.1: Illustration of an hyperspectral cube, spectral pixel and a spectral layer.

An hyperspectral system 22.1 acquired radiance, each pixel contains fine spectral information fine that depends of:

- Spectrum of the light source (in practice, the sun) and atmospheric disturbances.
- Spectral responses of different materials in the overlap zone and of the nature of the mixture.

Preliminary treatments allow to perform atmospheric correction for estimating a reflectance cube spectral by subtraction of information extrinsic of the scene (see also 12.2).

22.1 Unmixing

22.1.1 Linear mixing model

Reflectance information depends only of the materials spectral responses in the scene. When the mixture between materials is macroscopic, the linear mixing model of spectra is generally admitted. In this case, the image typically looks like this:

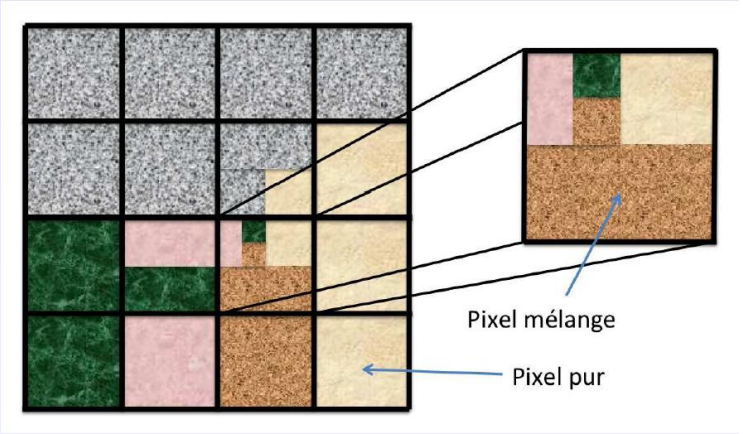


Figure 22.2: Zone which verify the LM model.

We notice 22.2 the presence of pure pixels, and pixel-blending. The LMM acknowledges that reflectance spectrum associated with each pixel is a linear combination of pure materials in the recovery area, commonly known as “”endmembers. This is illustrated in 22.3

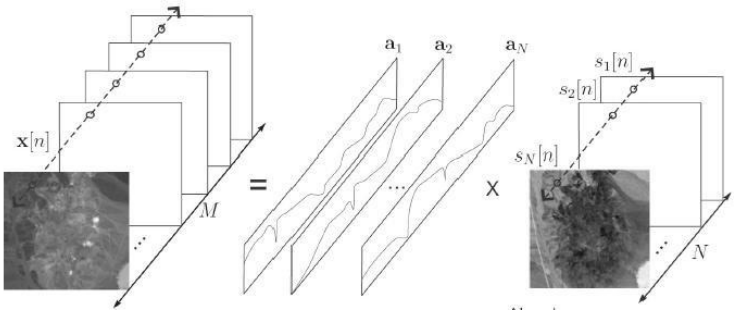


Figure 22.3: Decomposition of a hyperspectral cube according to the LMM.

The “ left” term represents the different spectral bands of data cube. The “ right” term represents a “ product” between the reflectance spectra of endmembers and their repective abundances. Abundance

band of endmembers is image grayscale between 0 and 1. The pixel i of the abundance band of endmember j is s_{ji}. This value is the abundance of endmember j in the pixel i. Under certain conditions [62], this value can be interpreted as the ratio surface of the material in the overlap zone (22.2). In practice, one can reasonably expect that:

- a limit number of pure materials compose the scene.
- the scene contains pure pixels if the spatial resolution is sufficient and do not necessarily contains them otherwise.

Many techniques of unmixing in hyperspectral image analysis are based on geometric approach where each pixel is seen as a spectral vector of L (number of spectral bands). The spectral bands can then be written as vectors.

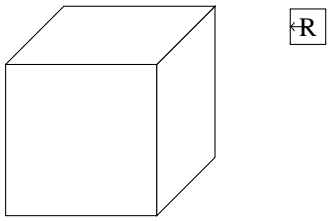


Figure 22.4: "Vectorization" of hyperspectral cube. The spectral pixels are stored in the columns of the matrix R and, in equivalently, the spectral bands are assigned to the lines of R.

By deduction of 22.3 et de 22.4, the LMM needs to decompose R as:

$$R = A.S + N = X + N$$

J is the number of endmembers and the number of spectral pixels I:

- J columns of the matrix A contain the spectra of endmembers.
- J rows of the matrix S contain the abundance maps vectorized, we call the columns vectors of abundances of matrix S.
- The matrix N, of dimensions LXI is a matrix of additive noise.

The unmixing problem is to estimate matrices A and S from R or possibly of $\ddot{\text{X}}$, an estimate of the denoised matrix signal.

Several physical constraints can be taken into account to solve the unmixing problem:

- C1: reflectance spectra are positives (non negative matrix A).

- C2: positivity abundances are positive (non-negative matrix S).
- C3: additivity abundance (the sum of the coefficients of each column of the matrix S is 1).
- Independence between the "algebraic spectral vectors" of endmembers associated with linearity and mixtures of spectra, so that the simplex property described in paragraph below.

22.1.2 Simplex

Recent unmixing algorithms based on the "property of simplex." In a vector space of dimension $J-1$, we can associate to J vectors algebrically independent, J points which define the vertices of a J-simplex 22.5.

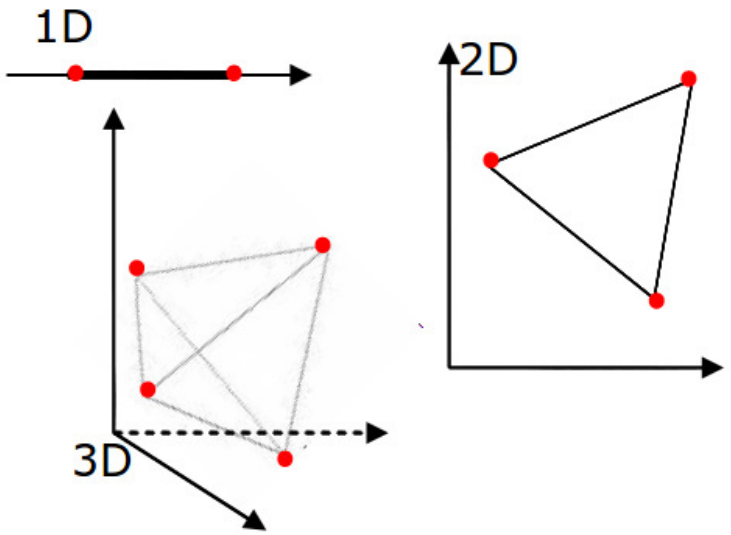


Figure 22.5: Illustration of a 2-simplex, a 3-simplex and a 4-simplex.

Hyperspectral cube of L bands, based on J endmembers, may be contained in a affine subspace of dimension $J-1$. A relevant subspace in the sense of signal-to-noise ratio is generally obtained by Principal Component Analysis (PCA) 14.7. In practice, the $J-1$ eigenvectors associated with highest values are the columns of a projection matrix V of dimension $(Lx(J-1))$. Reduced data Z, of dimensions $((J-1)xI)$ are obtained by the operation: $Z = V^T(\tilde{R})$

where each column of $\tilde{R}$ where the average spectrum is substracted, generally estimated under maximum likelihood. In the subspace carrying the column-vectors Z, endmembers spectra oare associated to the top of the simplex. If the noise is negligible, the simplex circumscribed reduced data.

This property shows that the endmembers research are the vertices of a simplex that circumscribes the data. However, an infinity of different simplices can identify the same data set. In fact, the

problem of unmixing generally does not have a unique solution. This degeneration can also be demonstrated by the formalism of the non-negative matrices factorization [3].

It is therefore necessary to choose the most physically relevant solution. All unmixing techniques based on this simplex property admit that the best solution is defined by the allowable minimum volume simplex, or the notion of volume is extended to all finite dimensions (possibly different from 3).

22.1.3 State of the art unmixing algorithms selection

The more recent linear unmixing algorithms exploit the simplex property. It is possible to classify these methods into several families:

Family 1

A first family of unmixing algorithms are based on research of the endmembers "among" data. This means that a minimum of one pure pixel must be associated with each endmembers. If this hypothesis is not verified, it will produce an estimation error of the endmembers spectra. The historical advantage of these algorithms are their low algorithmic complexity. The three best known are :

- PPI (Pixel Purity Index)
- VCA NFINDER (Vertex Component Analysis) [96]

In addition to its success recognized by the community and very competitive algorithmic complexity, the endmembers estimation is unbiased in absence of noise (and when there are pure pixels).

VCA The VCA algorithm is systematically used to initialize various studied algorithms (except MVES, based on a different initialization).

Important elements on the operation of VCA:

- The VCA algorithm is based on iterative projections of the data orthogonal to the subspace already held by the endmembers.
- Biaised when degree of purity is lower than 1.

Family 2

A second family is composed of algorithms which are looking for the simplex of minimum volume circumscribing the data. Phase initialization consists in determining an initial simplex any circumscribing the data. Then, a numerical optimization scheme minimizes a functional, increasing

function of the volume generalized, itself dependent of estimated endmembersin the current iteration. The optimization scheme is constrained by the fact that the data have remained on the simplex and possibly by constraints C1, C2 and C3.

Existing algorithms are:

- MVSA (Minimum Volume Simplex Analysis) [86].
- MVES (Minimum Volume Encosing Simplex) [Chan2009].
- SISAL (Simplex Identification via Split Augmented Lagrangian) [13].

Main differences between algorithms are:

- The numerical optimization scheme.
- The way constraints are taken into account.

These issues impact the computational complexity and the precision of the estimation.

MVSA [86] MVSA key points:

- Initialization by VCA.
- All spectral pixels included in the simplex estimate (approximatively) by VCA does not impact the constraint of data to belong to the researched simplex, they are simply delete the data used in the minimization of the simplex to reduce the algorithmic complexity.
- The highly developed optimization technique uses sequential quadratic programming (Sequential Quadratic Programming - SQP) and more specifically of the category “Quasi-Newton”under constraint.

MVES [23] MVES key points:

- Initialization by non-trivial iterative method (LP Linear Programming for Linear Programming), different from VCA.
- Resolution of problem by LP.

SISAL [13] SISAL key points:

- Initialisation by VCA.
- Selection of similar spectral pixels as MVSA to reduce computational complexity.

- Advanced optimization technique combining multiple features.
  - Decomposition of the non convex problem in convex set of problems.
  - Development of a specific method of separation of variables for considering Lagrangian increases with a good design properties.

Family 3

Non negative matrix factorization algorithms (NMF for Non-negative Matrix Factorization). The purpose of this branch of applied mathematics is to factor a non-negative matrix, X in our case, into a product of non negative matrices: AS by minimizing a distance between X and AS and with an adapted regularization to lift the degeneration in an appropriate manner adapted to the physical problems associated with unmixing.

MDMD-NMF [63]

Key points of MDMD-NMF:

- VCA initialization.
- Minimizing the norm of standard Frobenius with a spectral regularization and a regularization "Space"(the matrix of abundances).
  - Minimum spectral Dispersion: the spectral regularization encourages the variance of coefficients of a spectrum of endmembers to be low.
  - Maximum spatial dispersion: the spatial regularization encourages the vector of abundances to occupy all the admissible parts (more information in [62]). it presents a certain analogy with the minimum volume constraint.

Further remarks

Algorithms of families 1 and 2 estimate " only" the spectra of endmembers. The estimated abundance maps held *a posteri* and requires the application of an algorithm like Fully Constrained Least Square (FCLS) `otb::FCLSUnmixingImageFilter` [57]. VSS includes an specific algorithm for the estimation of the abundances. The unmixing is a general non-convex problem, which explains the importance of the initialization of algorithms.

Overview of algorithms and related physical constraints:

	VCA	MVSA	MVES	SISAL	MDMD
C1 ($A > 0$)	mute	mute	mute	mute	hard
C2 ($S > 0$)	mute	hard	hard	soft	hard
C3 (additivity)	Mute (FCLS)	hard	hard	hard	soft
simplex	Endmembers in the data	Circumscribed to data	Circumscribed to data	Circumscribed to data	Indirectly by "space" regularization

Basic hyperspectral unmixing example

The source code for this example can be found in the file `Examples/Hyperspectral/HyperspectralUnmixingExample.cxx`.

This example illustrates the use of the `otb::VcaImageFilter` and `otb::UnConstrainedLeastSquareImageFilter`. The VCA filter computes endmembers using the Vertex Component Analysis and UCLS performs unmixing on the input image using these endmembers.

The first step required to use these filters is to include its header files.

```
#include "otbVcaImageFilter.h"
#include "otbUnConstrainedLeastSquareImageFilter.h"
```

We start by defining the types for the images and the reader and the writer. We choose to work with a `otb::VectorImage`, since we will produce a multi-channel image (the principal components) from a multi-channel input image.

```
typedef otb::VectorImage<PixelType, Dimension>  ImageType;
typedef otb::ImageFileReader<ImageType>         ReaderType;
typedef otb::ImageFileWriter<ImageType>         WriterType;
```

We instantiate now the image reader and we set the image file name.

```
ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(infname);
```

For now we need to rescale the input image between 0 and 1 to perform the unmixing algorithm. We use the `otb::VectorRescaleIntensityImageFilter`.

```
RescalerType::Pointer         rescaler = RescalerType::New();
rescaler->SetInput(reader->GetOutput());

ImageType::PixelType minPixel, maxPixel;
minPixel.SetSize(reader->GetOutput()->GetNumberOfComponentsPerPixel());
maxPixel.SetSize(reader->GetOutput()->GetNumberOfComponentsPerPixel());
minPixel.Fill(0.);
```

```
maxPixel.Fill(1.);

rescaler->SetOutputMinimum(minPixel);
rescaler->SetOutputMaximum(maxPixel);
```

We define the type for the VCA filter. It is templated over the input image type. The only parameter is the number of endmembers which needs to be estimated. We can now the instantiate the filter.

```
typedef otb::VCAImageFilter<ImageType>                    VCAFilterType;
VCAFilterType::Pointer vca = VCAFilterType::New();

vca->SetNumberOfEndmembers(estimateNumberOfEndmembers);
vca->SetInput(rescaler->GetOutput());
```

We transform the output estimate endmembers to a matrix representation

```
VectorImageToMatrixImageFilterType::Pointer
  endMember2Matrix = VectorImageToMatrixImageFilterType::New();
endMember2Matrix->SetInput(vca->GetOutput());
endMember2Matrix->Update();
```

We can now procedd to the unmixing algorithm.Parameters needed are the input image and the endmembers matrix.

```
typedef otb::UnConstrainedLeastSquareImageFilter<ImageType, ImageType, double> UCLSUnmixingF
UCLSUnmixingFilterType::Pointer
  unmixer = UCLSUnmixingFilterType::New();
unmixer->SetInput(rescaler->GetOutput());
unmixer->SetMatrix(endMember2Matrix->GetMatrix());
```

We now instantiate the writer and set the file name for the output image and trigger the unmixing computation with the `Update()` of the writer.

```
WriterType::Pointer  writer = WriterType::New();
writer->SetInput(unmixer->GetOutput());
writer->SetFileName(outfname);
writer->Update();
```

Figure 22.6 shows the result of applying unmixing to an AVIRIS image (220 bands). This dataset is freely available at `http://www.ehu.es/ccwintco/index.php/Hyperspectral_Remote_Sensing_ScenesIndian_Pines`

22.2 Dimensionality reduction

Please refer to chapter 18, page 421 for a presentation of dimension reduction methods available in OTB.

Figure 22.6: Result of applying the `otb::VcaImageFilter` and `otb::UnConstrainedLeastSquareImageFilter` to an image. From left to right and top to bottom: first abundance map band, second abundance map band, third abundance map band.

22.3 Anomaly detection

By definition, an anomaly in a scene is an element that does not expect to find. The unusual element is likely different from its environment and its presence is in the minority scene. Typically, a vehicle in natural environment, a rock in a field, a wooden hut in a forest are anomalies that can be desired to detect using a hyperspectral imaging. This implies that the spectral response of the anomaly can be discriminated in the spectral response of "background clutter". This also implies that the pixels associated to anomalies, the anomalous pixels are sufficiently rare and/or punctual to be considered as such. These properties can be viewed as spectral and spatial hypotheses on which the techniques of detection anomalies in hyperspectral images rely on.

Literature on hyperspectral imaging generally distinguishes target detection and detection anomalies:

- We speak of detection of targets when the spectral response element of the research is used as input to the detection algorithm. This is an *a priori* information that can, in theory, allow to construct algorithms with very high detection score, such as for example the Adaptive Matched Filter (AMF) or Adaptive Cosine/Coherence Estimator (ACE). Nevertheless, thin enough knowledge of the researched spectrum is a difficult information to hold in practice, leading the use of anomaly detection algorithms.
- We speak of detection of anomalies (or outliers) when the spectrum of the unusual element is not required by the algorithm. For this reason, we often associate the term "Unsupervised" detection. Nevertheless, these algorithms depend generally of "structural" parameters. For example, in the case of detection on a sliding window, selecting the right dimensions is based on an *a priori* knowledge of the anomalies size. We focus here on algorithms for **anomaly detection.**

In 22.7, we introduce some notions that will be useful later. Anomaly detection algorithms have an image as input and consider a map serving as a detection tool for making a decision. A adaptive

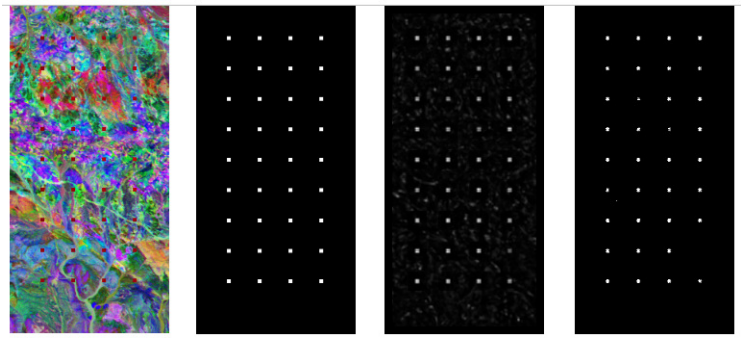


Figure 22.7: Notions on detection: ground truth mask, map detection, face detection.

thresholding provides a estimated mask detection that we hope is the most similar possible as the ground truth mask, unknown in practice.

Two approaches dominate the state of the art in anomaly detection in hyperspectral images. Methods which use Pursuit Projection (PP) and methods based on a probabilistic modelization of the background and possibly of the target class with statistical hypothesis tests. The PP consists in projecting linearly spectral pixels on vectors wi which optimizes a criterion sensitive to the presence of anomalies (like Kurtosis). This gives a series of maps of projections where anomalies contrast very strongly with the background. But the automatic estimation of map detection have also major difficulties, including:

- How many projectors should I consider?
- What (s) projector (s) to choose?
- How to manage an inhomogeneous background?
- Detection performances varies with the spatial dimensions of the image (number of samples)
- These algorithms usually do not have a structure allowing parallelization
- These algorithms do not generally have a "constant false alarm rate".

Algorithms described here are RX (presented in the first version in [114] and GMRF [122]. They are based on probability models, statistics and hypothesis tests and sliding window. These approaches consist in answering the following question : "The pixel (or set of neighboring pixels) tests looks like background pixels?", by a process of test statistics. More fully, this approach requires:

- A model for the background
- The choice of a statistic test

- Eventually, a model for the class “anomaly”
- Estimators for the parameters *a priori* unknown
- Hypothesis of homogeneity for a satisfactory compromise between:
  - The number of samples compared to the number of estimate parameters
  - The homogeneity, including the background
  - Algorithmic complexity (although the algorithms considered are highly parallelizable)

Principle of RX and GMRF can be resume with 22.8.

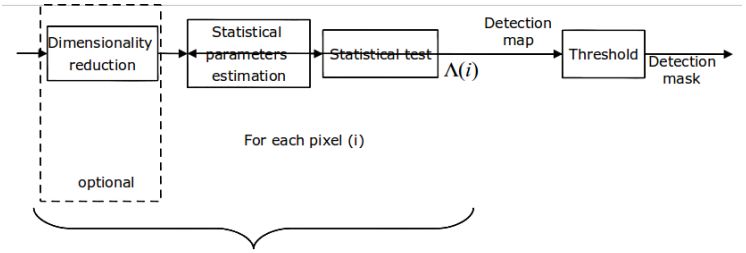


Figure 22.8: Basic workflow of anomaly detection in hyperspectral images.

An optional first step is to reduce the size of spectral data while maintaining information related to anomalies. Then, the spectral pixels are tested one by oneturn (parallelizable task). The pixel test works on a sliding window (see 22.9). This window consists of two sub windows, centered on the pixel test of dimensions L and LL, with $L < LL$.

- Pixels belonging to the annulus formed the class “local background”. The statistical parameters of the background, required by statistical tests, are estimated from these spectral pixels. One of the challenges is to find a compromise on the thickness of the annulus (and therefore the number statistical sampling) where:
  - If the annulus is too thick, the local background is no longer homogeneous
  - If the number of samples is too low, the precision of the statistical estimation of the model parameters for the background is too low
- Pixels of the central part of the sliding window belong to the class “unknown”. If the test pixel (central pixel) is an anomaly, it is possible that its neighbors pixels are also anomalies, which imply to not to choose a too small value for L if it is known that anomalies can be distribute over several pixels.

Once all the parameters are estimated, a statistical test is performed and assigns a value $\Lambda(i)$ to the tested pixel i. A map of detection is thus formed.

The RX algorithm is available in OTB through the `otb::LocalRxDetectorFilter` class.

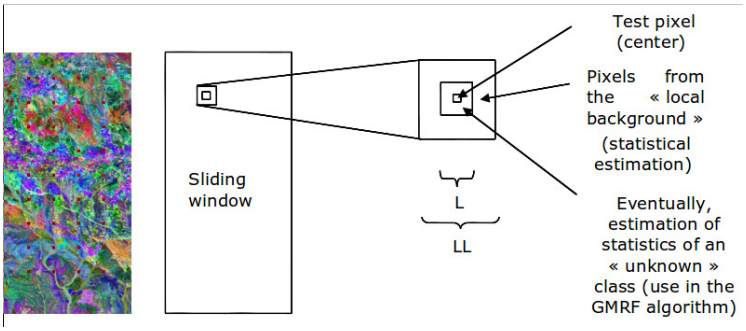


Figure 22.9: Principle of the sliding window and definitions of parameters L and LL of the sliding window. RX algorithms and GMRF, taken herein in the following sections.

CHAPTER

TWENTYTHREE

IMAGE VISUALIZATION AND OUTPUT

After processing your images with OTB, you probably want to see the result. As it is quite straightforward in some situation, if can be a bit trickier in other. For example, some filters will give you a list of polygons as an output. Other can return an image with each region labelled by a unique index. In this section we are going to provide few examples to help you produce beautiful output ready to be included in your publications/presentations.

23.1 Images

23.1.1 Grey Level Images

The source code for this example can be found in the file
`Examples/BasicFilters/ScalingFilterExample.cxx`.

On one hand, satellite images are commonly coded on more than 8 bits to provide the dynamic range required from shadows to clouds. On the other hand, image formats in use for printing and display are usually limited to 8 bits. We need to convert the value to enable a proper display. This is usually done using linear scaling. Of course, you have to be aware that some information is lost in the process.

The `itk::RescaleIntensityImageFilter` is used to rescale the value:

```
typedef itk::RescaleIntensityImageFilter<InputImageType,
    OutputImageType> RescalerType;
RescalerType::Pointer rescaler = RescalerType::New();
rescaler->SetInput(reader->GetOutput());
```

Figure 23.1 illustrates the difference between a proper scaling and a simple truncation of the value and demonstrates why it is important to keep this in mind.

Figure 23.1: On the left, the image obtained by truncated pixel values at the dynamic acceptable for a png file (between 0 and 255). On the right, the same image with a proper rescaling

23.1.2 Multiband Images

The source code for this example can be found in the file
`Examples/BasicFilters/PrintableImageFilterExample.cxx`.

Most of the time, satellite images have more than three spectral bands. As we are only able to see three colors (red, green and blue), we have to find a way to represent these images using only three bands. This is called creating a color composition.

Of course, any color composition will not be able to render all the information available in the original image. As a consequence, sometimes, creating more than one color composition will be necessary.

If you want to obtain an image with natural colors, you have to match the wavelength captured by the satellite with those captured by your eye: thus matching the red band with the red color, etc.

Some satellites (SPOT 5 is an example) do not acquire all the *human* spectral bands: the blue can be missing and replaced by some other wavelength of interest for a specific application. In these situations, another mapping has to be created. That's why, the vegetation often appears in red in satellite images (see on left of figure 23.2).

The band order in the image products can be also quite tricky. It could be in the wavelength order, as it is the case for Quickbird (1: Blue, 2: Green, 3: Red, 4: NIR), in this case, you have to be carefull to reverse the order if you want a natural display. It could also be reverse to facilitate direct viewing, as for SPOT5 (1: NIR, 2: Red, 3: Green, 4: SWIR) but in this situations you have to be careful when you process the image.

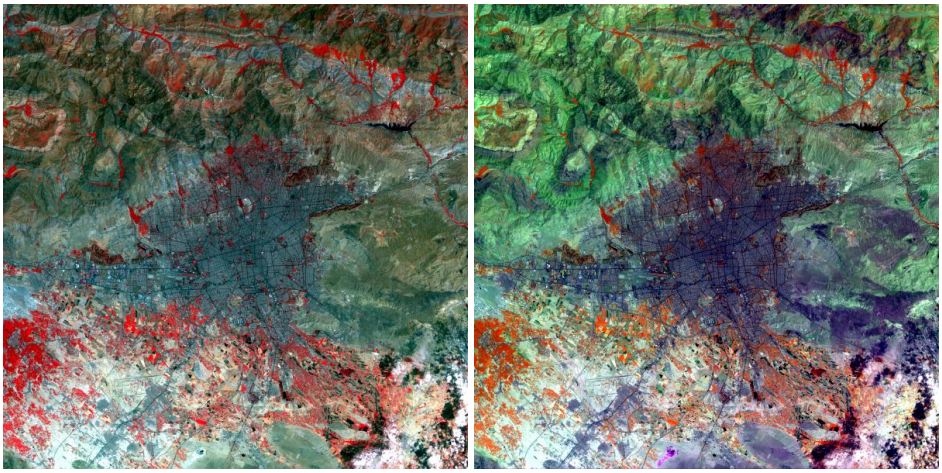


Figure 23.2: On the left, a classic SPOT5 combination: XS3 in red, XS2 in green and XS1 in blue. On the right another composition: XS3 in red, XS4 in green and XS2 in blue.

To easily convert the image to a *printable* format, i.e. 3 bands `unsigned char` value, you can use the `otb::PrintableImageFilter`.

```
typedef otb::PrintableImageFilter<InputImageType> PrintableFilterType;
PrintableFilterType::Pointer printableImageFilter = PrintableFilterType::New();

printableImageFilter->SetInput(reader->GetOutput());
printableImageFilter->SetChannel(redChannelNumber);
printableImageFilter->SetChannel(greenChannelNumber);
printableImageFilter->SetChannel(blueChannelNumber);
```

When you create the writer to plug at the output of the `printableImageFilter` you may want to use the direct type definition as it is a good way to avoid mismatch:

```
typedef PrintableFilterType::OutputImageType          OutputImageType;
typedef otb::ImageFileWriter<OutputImageType> WriterType;
```

Figure 23.2 illustrates different color compositions for a SPOT 5 image.

23.1.3 Indexed Images

The source code for this example can be found in the file `Examples/BasicFilters/IndexedToRGBExample.cxx`.

Some algorithms produce an indexed image as output. In such images, each pixel is given a value according to the region number it belongs to. This value starting at 0 or 1 is usually an integer value. Often, such images are produced by segmentation or classification algorithms.

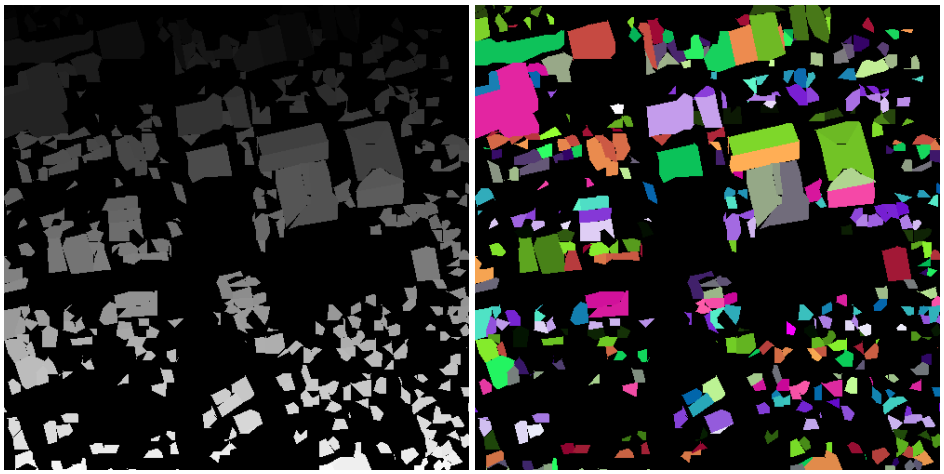


Figure 23.3: The original indexed image (left) and the conversion to color image.

If such regions are easy to manipulate – it is easier and faster to compare two integers than a RGB value – it is different when it comes to displaying the results.

Here we present a convient way to convert such indexed image to a color image. In such conversion, it is important to ensure that neighborhood region, which are likely to have consecutive number have easily dicernable colors. This is done randomly using a hash function by the `itk::ScalarToRGBPixelFunctor`.

The `itk::UnaryFunctorImageFilter` is the filter in charge of calling the functor we specify to do the work for each pixel. Here it is the `itk::ScalarToRGBPixelFunctor`.

```
typedef itk::Functor::ScalarToRGBPixelFunctor<unsigned long>
ColorMapFunctorType;
typedef itk::UnaryFunctorImageFilter<ImageType, RGBImageType,
    ColorMapFunctorType> ColorMapFilterType;
ColorMapFilterType::Pointer colormapper = ColorMapFilterType::New();

colormapper->SetInput(reader->GetOutput());
```

Figure 23.3 shows the result of the conversion from an indexed image to a color image.

23.1.4 Altitude Images

The source code for this example can be found in the file
`Examples/BasicFilters/DEMToRainbowExample.cxx`.

In some situation, it is desirable to represent a gray level image in color for easier interpretation. This is particularly the case if pixel values in the image are used to represent some data such as

elevation, deformation map, interferogram. In this case, it is important to ensure that similar values will get similar colors. You can notice how this requirement differ from the previous case.

The following example illustrates the use of the otb::DEMToImageGenerator class combined with the otb::ScalarToRainbowRGBPixelFunctor. You can refer to the source code or to section 7.1 for the DEM conversion to image, we will focus on the color conversion part here.

As in the previous example the itk::ScalarToRGBColormapImageFilter is the filter in charge of calling the functor we specify to do the work for each pixel. Here it is the otb::ScalarToRainbowRGBPixelFunctor.

```
typedef itk::ScalarToRGBColormapImageFilter<ImageType,
    RGBImageType> ColorMapFilterType;
ColorMapFilterType::Pointer colormapper = ColorMapFilterType::New();
colormapper->UseInputImageExtremaForScalingOff();

if (argc == 9)
  {
  typedef otb::Functor::ScalarToRainbowRGBPixelFunctor<PixelType,
      RGBPixelType>
  ColorMapFunctorType;
  ColorMapFunctorType::Pointer colormap = ColorMapFunctorType::New();
  colormap->SetMinimumInputValue(0);
  colormap->SetMaximumInputValue(4000);
  colormapper->SetColormap(colormap);
  }
```

And we connect the color mapper filter with the filter producing the image of the DEM:

```
colormapper->SetInput(demToImage->GetOutput());
```

Figure 23.4 shows effect of applying the filter to a gray level image.

The source code for this example can be found in the file
Examples/BasicFilters/HillShadingExample.cxx.

Visualization of digital elevation models (DEM) is often more intuitive by simulating a lighting source and generating the corresponding shadows. This principle is called hill shading.

Using a simple functor otb::HillShadingFunctor and the dem image generated using the otb::DEMToImageGenerator (refer to 7.1) you can easily obtain a representation of the DEM. Better yet, using the otb::ScalarToRainbowRGBPixelFunctor, combined with the otb::ReliefColormapFunctor you can easily generate the classic elevation maps.

This example will focus on the shading itself.

After generating the dem image as in the DEMToImageGenerator example, you can declare the hill shading mechanism. The hill shading is implemented as a functor doing some operations in its neighborhood. A convenient filter called otb::HillShadingFilter is defined around this mechanism.

```
typedef otb::HillShadingFilter<ImageType, ImageType> HillShadingFilterType;
```

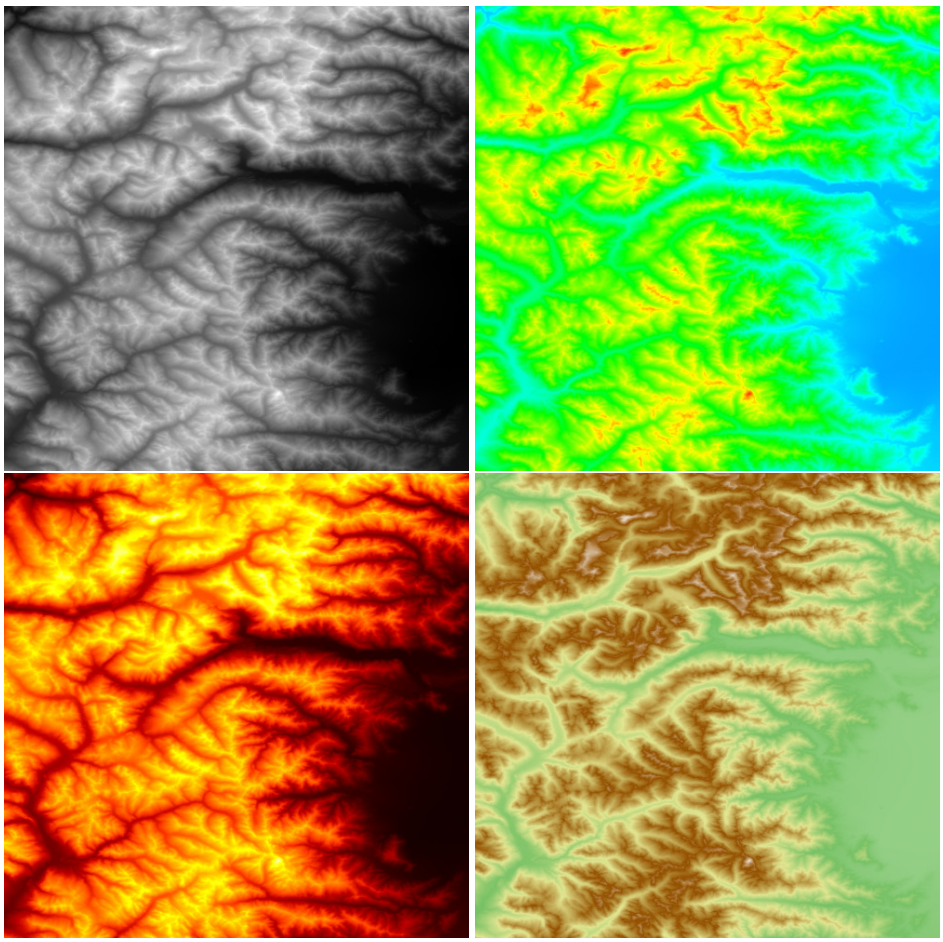


Figure 23.4: The gray level DEM extracted from SRTM data (top-left) and the same area in color representation.

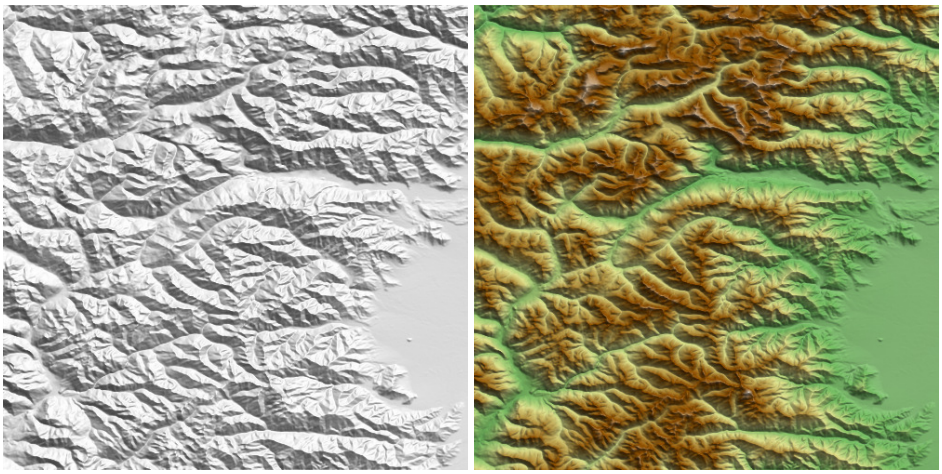


Figure 23.5: Hill shading obtained from SRTM data (left) and combined with the color representation (right)

```
HillShadingFilterType::Pointer hillShading = HillShadingFilterType::New();
hillShading->SetRadius(1);
hillShading->SetInput(demToImage->GetOutput());
```

Figure 23.5 shows the hill shading result from SRTM data.

CHAPTER

TWENTYFOUR

ONLINE DATA

With almost every computer connected to the Internet, the amount of online information is steadily growing. It is quite easy to retrieve valuable information. OTB has a few experimental classes for this purpose.

For these examples to work, you need to have OTB compiled with the `OTB_USE_CURL` option to `ON` (and the curl library installed somewhere).

Let's see what we can do.

24.1 Name to Coordinates

The source code for this example can be found in the file `Examples/Projections/PlaceNameToLonLatExample.cxx`.

This example will show how to retrieve the longitude and latitude from a place using the name of the city or the address. For that, we will use the `otb::PlaceNameToLonLat` class.

```
#include "otbPlaceNameToLonLat.h"
```

You instantiate the class and pass the name you want to look for as a std::string to the SetPlaceName method.

The call to evaluate will trigger the retrival process.

```
otb::PlaceNameToLonLat::Pointer pn2LL = otb::PlaceNameToLonLat::New();
pn2LL->SetPlaceName(std::string(argv[1]));
pn2LL->Evaluate();
```

To get the data, you can simply call the GetLon and GetLat methods.

```
double lon = pn2LL->GetLon();
double lat = pn2LL->GetLat();
```

```
  std::cout << "Latitude: " << lat << std::endl;
  std::cout << "Longitude: " << lon << std::endl;
```

If you tried with a string such as "Toulouse" – a city where the heart of OTB relies – you should obtain something like:

```
Latitude: 43.6044
Longitude: 1.44295
```

24.2 Open Street Map

The power of sharing which is a driving force in open source software such as OTB can also be demonstrated for data collection. One good example is Open Street Map (`http://www.openstreetmap.org/`).

In this project, hundreds of thousands of users upload GPS data and draw maps of their surroundings. The coverage is impressive and this data is freely available.

It is even possible to get the vector data (not covered yet by OTB), but here we will focus on retrieving some nice maps for any place in the world. The following example describes the method. This part is pretty experimental and the code is not as polished as the rest of the library. You've been warned!

The source code for this example can be found in the file `Examples/IO/TileMapImageIOExample.cxx`.

First, we need to include several headers. There will be a bit of manual work going on here.

```
#include "itkRGBPixel.h"
#include "otbImage.h"
#include "otbImageFileReader.h"
#include "otbTileMapImageIO.h"
#include "otbInverseSensorModel.h"
#include "otbForwardSensorModel.h"
#include "otbExtractROI.h"
#include "otbImageFileWriter.h"
#include "otbTileMapTransform.h"
#include "otbWorldFile.h"
```

We retrieve the input parameters:

- the input filename is a simple text file specifying the access modality to open street map data;
- the output file is the image where you want to save the result;
- the cache directory is necessary to keep the data retrieved from the internet. It can also be reused to minimize network access;

- longitude of the center of the scene;
- latitude of the center of the scene;
- depth which is inversely related to the resolution: when you increase the depth by one, you divide the resolution by two.

```
std::string inputFilename = argv[1];
std::string outputFilename = argv[2];
std::string cacheDirectory = argv[3];
double      lon = atof(argv[4]);
double      lat = atof(argv[5]);
int         depth = atoi(argv[6]);
```

We now instantiate the reader. As some parameters need to be given to the IO which is an `otb::TileMapImageIO`, we need to manually create it:

```
typedef itk::RGBPixel<unsigned char>    RGBPixelType;
typedef otb::Image<RGBPixelType, 2>     ImageType;
typedef otb::ImageFileReader<ImageType> ReaderType;
typedef otb::TileMapImageIO             ImageIOType;

ImageIOType::Pointer tileIO = ImageIOType::New();
ReaderType::Pointer  readerTile = ReaderType::New();
tileIO->SetDepth(depth);
tileIO->SetCacheDirectory(cacheDirectory);
readerTile->SetImageIO(tileIO);
readerTile->SetFileName(inputFilename);
readerTile->UpdateOutputInformation();
```

Now, we potentially have an image of several Peta-Bytes covering the whole world in the reader that's why we don't want to do an update before extracting a specific area.

The coordinates are referred with an origin at the North Pole and the change date meridian in Mercator projection. So we need to translate the latitude and the longitude in this funny coordinate system:

```
typedef otb::TileMapTransform<otb::TransformDirection::FORWARD> TransformType;
TransformType::Pointer transform = TransformType::New();
transform->SetDepth(depth);

typedef itk::Point <double, 2> PointType;
PointType lonLatPoint;
lonLatPoint[0] = lon;
lonLatPoint[1] = lat;

PointType tilePoint;
tilePoint = transform->TransformPoint(lonLatPoint);
```

This enables us to use the `otb::ExtractROI` to retrieve only the area of interest and to avoid crashing our memory-limited computer.

```
long int startX = static_cast<long int>(tilePoint[0]);
long int startY = static_cast<long int>(tilePoint[1]);
long int sizeX = 500;
long int sizeY = 500;

std::cerr << startX << ", " << startY << std::endl;
std::cerr << sizeX << ", " << sizeY << std::endl;

typedef otb::ExtractROI<RGBPixelType,  RGBPixelType> ExtractROIFilterType;
ExtractROIFilterType::Pointer extractROIOsmFilter = ExtractROIFilterType::New();
extractROIOsmFilter->SetStartX(startX - sizeX / 2);
extractROIOsmFilter->SetStartY(startY - sizeY / 2);
extractROIOsmFilter->SetSizeX(sizeX);
extractROIOsmFilter->SetSizeY(sizeY);

extractROIOsmFilter->SetInput(readerTile->GetOutput());
```

Finally, we just plug this to the writer to save our nice map of the area:

```
typedef otb::ImageFileWriter<ImageType> WriterType;
WriterType::Pointer writer = WriterType::New();
writer->SetFileName(outputFilename);
writer->SetInput(extractROIOsmFilter->GetOutput());
writer->Update();
```

We also want to create the associated world file to be able to use this new image in a GIS system. For this, we need to compute the coordinates of the top left corner and the spacing in latitude and longitude.

For that, we use the inverse transform to convert the corner coordinates into latitude and longitude.

```
typedef otb::TileMapTransform<otb::TransformDirection::INVERSE> InverseTransformType;
InverseTransformType::Pointer transformInverse = InverseTransformType::New();
transformInverse->SetDepth(depth);


double lonUL, latUL, lonSpacing, latSpacing;

tilePoint[0] = startX - sizeX / 2;
tilePoint[1] = startY - sizeY / 2;
lonLatPoint = transformInverse->TransformPoint(tilePoint);
lonUL = lonLatPoint[0];
latUL = lonLatPoint[1];
tilePoint[0] = startX + sizeX / 2;
tilePoint[1] = startY + sizeY / 2;
lonLatPoint = transformInverse->TransformPoint(tilePoint);
lonSpacing = (lonLatPoint[0] - lonUL) / (sizeX - 1);
latSpacing = (lonLatPoint[1] - latUL) / (sizeY - 1);
```

Now that we have all the information, we can write the world file which has the wld extension. This is a simple text file containing the coordinates of the center of the top left pixel and the x and y spacing.

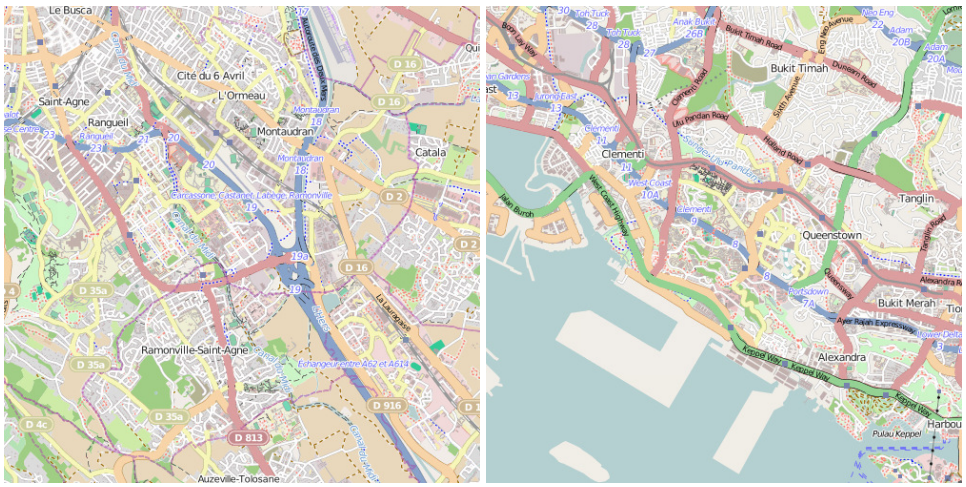


Figure 24.1: Map created from open street map showing the OTB headquaters

```
otb::WorldFile::Pointer worldFile = otb::WorldFile::New();
worldFile->SetImageFilename(outputFilename);
worldFile->SetLonOrigin(lonUL);
worldFile->SetLatOrigin(latUL);
worldFile->SetLonSpacing(lonSpacing);
worldFile->SetLatSpacing(latSpacing);
worldFile->Update();
```

Figure 24.1 shows the output images created from open street map data.

If your street is missing, go and improve the map by adding it yourself.

Part IV

Developer's guide

CHAPTER

TWENTYFIVE

ITERATORS

This chapter introduces the *image iterator*, an important generic programming construct for image processing in ITK. An iterator is a generalization of the familiar C programming language pointer used to reference data in memory. ITK has a wide variety of image iterators, some of which are highly specialized to simplify common image processing tasks.

The next section is a brief introduction that defines iterators in the context of ITK. Section 25.2 describes the programming interface common to most ITK image iterators. Sections 25.3–25.4 document specific ITK iterator types and provide examples of how they are used.

25.1 Introduction

Generic programming models define functionally independent components called *containers* and *algorithms*. Container objects store data and algorithms operate on data. To access data in containers, algorithms use a third class of objects called *iterators*. An iterator is an abstraction of a memory pointer. Every container type must define its own iterator type, but all iterators are written to provide a common interface so that algorithm code can reference data in a generic way and maintain functional independence from containers.

The iterator is so named because it is used for *iterative*, sequential access of container values. Iterators appear in `for` and `while` loop constructs, visiting each data point in turn. A C pointer, for example, is a type of iterator. It can be moved forward (incremented) and backward (decremented) through memory to sequentially reference elements of an array. Many iterator implementations have an interface similar to a C pointer.

In ITK we use iterators to write generic image processing code for images instantiated with different combinations of pixel type, pixel container type, and dimensionality. Because ITK image iterators are specifically designed to work with *image* containers, their interface and implementation is optimized for image processing tasks. Using the ITK iterators instead of accessing data directly through the `otb::Image` interface has many advantages. Code is more compact and often generalizes automatically to higher dimensions, algorithms run much faster, and iterators simplify tasks such as

multithreading and neighborhood-based image processing.

25.2 Programming Interface

This section describes the standard ITK image iterator programming interface. Some specialized image iterators may deviate from this standard or provide additional methods.

25.2.1 Creating Iterators

All image iterators have at least one template parameter that is the image type over which they iterate. There is no restriction on the dimensionality of the image or on the pixel type of the image.

An iterator constructor requires at least two arguments, a smart pointer to the image to iterate across, and an image region. The image region, called the *iteration region*, is a rectilinear area in which iteration is constrained. The iteration region must be wholly contained within the image. More specifically, a valid iteration region is any subregion of the image within the current `BufferedRegion`. See Section 5.1 for more information on image regions.

There is a const and a non-const version of most ITK image iterators. A non-const iterator cannot be instantiated on a non-const image pointer. Const versions of iterators may read, but may not write pixel values.

Here is a simple example that defines and constructs a simple image iterator for an `otb::Image`.

```
typedef otb::Image<float, 3> ImageType;
typedef itk::ImageRegionConstIterator< ImageType > ConstIteratorType;
typedef itk::ImageRegionIterator< ImageType > IteratorType;

ImageType::Pointer image = SomeFilter->GetOutput();

ConstIteratorType constIterator( image, image->GetRequestedRegion() );
IteratorType iterator( image, image->GetRequestedRegion() );
```

25.2.2 Moving Iterators

An iterator is described as *walking* its iteration region. At any time, the iterator will reference, or "point to", one pixel location in the N-dimensional (ND) image. *Forward iteration* goes from the beginning of the iteration region to the end of the iteration region. *Reverse iteration*, goes from just past the end of the region back to the beginning. There are two corresponding starting positions for iterators, the *begin* position and the *end* position. An iterator can be moved directly to either of these two positions using the following methods.

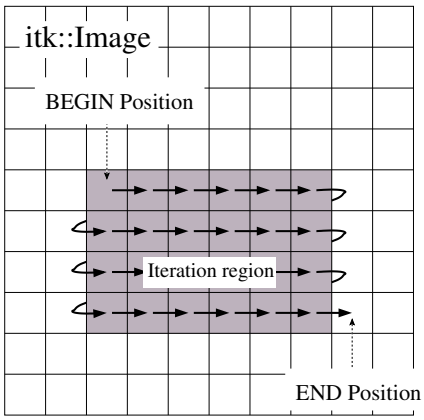


Figure 25.1: Normal path of an iterator through a 2D image. The iteration region is shown in a darker shade. An arrow denotes a single iterator step, the result of one ++ operation.

- **`GoToBegin()`** Points the iterator to the first valid data element in the region.
- **`GoToEnd()`** Points the iterator to *one position past* the last valid element in the region.

Note that the end position is not actually located within the iteration region. This is important to remember because attempting to dereference an iterator at its end position will have undefined results.

ITK iterators are moved back and forth across their iterations using the decrement and increment operators.

- **`operator++()`** Increments the iterator one position in the positive direction. Only the prefix increment operator is defined for ITK image iterators.
- **`operator--()`** Decrements the iterator one position in the negative direction. Only the prefix decrement operator is defined for ITK image iterators.

Figure 25.1 illustrates typical iteration over an image region. Most iterators increment and decrement in the direction of the fastest increasing image dimension, wrapping to the first position in the next higher dimension at region boundaries. In other words, an iterator first moves across columns, then down rows, then from slice to slice, and so on.

In addition to sequential iteration through the image, some iterators may define random access operators. Unlike the increment operators, random access operators may not be optimized for speed and require some knowledge of the dimensionality of the image and the extent of the iteration region to use properly.

- **operator+=(OffsetType)** Moves the iterator to the pixel position at the current index plus specified `itk::Offset`.
- **operator-=(OffsetType)** Moves the iterator to the pixel position at the current index minus specified Offset.
- **SetPosition(IndexType)** Moves the iterator to the given `itk::Index` position.

The `SetPosition()` method may be extremely slow for more complicated iterator types. In general, it should only be used for setting a starting iteration position, like you would use `GoToBegin()` or `GoToEnd()`.

Some iterators do not follow a predictable path through their iteration regions and have no fixed beginning or ending pixel locations. A conditional iterator, for example, visits pixels only if they have certain values or connectivities. Random iterators, increment and decrement to random locations and may even visit a given pixel location more than once.

An iterator can be queried to determine if it is at the end or the beginning of its iteration region.

- **bool IsAtEnd()** True if the iterator points to *one position past* the end of the iteration region.
- **bool IsAtBegin()** True if the iterator points to the first position in the iteration region. The method is typically used to test for the end of reverse iteration.

An iterator can also report its current image index position.

- **IndexType GetIndex()** Returns the Index of the image pixel that the iterator currently points to.

For efficiency, most ITK image iterators do not perform bounds checking. It is possible to move an iterator outside of its valid iteration region. Dereferencing an out-of-bounds iterator will produce undefined results.

25.2.3 Accessing Data

ITK image iterators define two basic methods for reading and writing pixel values.

- **PixelType Get()** Returns the value of the pixel at the iterator position.
- **void Set(PixelType)** Sets the value of the pixel at the iterator position. Not defined for const versions of iterators.

The `Get()` and `Set()` methods are inlined and optimized for speed so that their use is equivalent to dereferencing the image buffer directly. There are a few common cases, however, where using `Get()` and `Set()` do incur a penalty. Consider the following code, which fetches, modifies, and then writes a value back to the same pixel location.

```
it.Set( it.Get() + 1 );
```

As written, this code requires one more memory dereference than is necessary. Some iterators define a third data access method that avoids this penalty.

- **`PixelType &Value()`** Returns a reference to the pixel at the iterator position.

The `Value()` method can be used as either an lval or an rval in an expression. It has all the properties of `operator*`. The `Value()` method makes it possible to rewrite our example code more efficiently.

```
it.Value()++;
```

Consider using the `Value()` method instead of `Get()` or `Set()` when a call to `operator=` on a pixel is non-trivial, such as when working with vector pixels, and operations are done in-place in the image. The disadvantage of using `Value` is that it cannot support image adapters (see Section 26 on page 593 for more information about image adaptors).

25.2.4 Iteration Loops

Using the methods described in the previous sections, we can now write a simple example to do pixel-wise operations on an image. The following code calculates the squares of all values in an input image and writes them to an output image.

```
ConstIteratorType in( inputImage,   inputImage->GetRequestedRegion() );
IteratorType out( outputImage, inputImage->GetRequestedRegion() );

for ( in.GoToBegin(), out.GoToBegin(); !in.IsAtEnd(); ++in, ++out )
  {
  out.Set( in.Get() * in.Get() );
  }
```

Notice that both the input and output iterators are initialized over the same region, the `RequestedRegion` of `inputImage`. This is good practice because it ensures that the output iterator walks exactly the same set of pixel indices as the input iterator, but does not require that the output and input be the same size. The only requirement is that the input image must contain a region (a starting index and size) that matches the `RequestedRegion` of the output image.

Equivalent code can be written by iterating through the image in reverse. The syntax is slightly more awkward because the *end* of the iteration region is not a valid position and we can only test whether the iterator is strictly *equal* to its beginning position. It is often more convenient to write reverse iteration in a `while` loop.

```
in.GoToEnd();
out.GoToEnd();
while ( ! in.IsAtBegin() )
  {
  --in;
  --out;
  out.Set( in.Get() * in.Get() );
  }
```

25.3 Image Iterators

This section describes iterators that walk rectilinear image regions and reference a single pixel at a time. The `itk::ImageRegionIterator` is the most basic ITK image iterator and the first choice for most applications. The rest of the iterators in this section are specializations of ImageRegionIterator that are designed make common image processing tasks more efficient or easier to implement.

25.3.1 ImageRegionIterator

The source code for this example can be found in the file `Examples/Iterators/ImageRegionIterator.cxx`.

The `itk::ImageRegionIterator` is optimized for iteration speed and is the first choice for iterative, pixel-wise operations when location in the image is not important. ImageRegionIterator is the least specialized of the ITK image iterator classes. It implements all of the methods described in the preceding section.

The following example illustrates the use of `itk::ImageRegionConstIterator` and ImageRegionIterator. Most of the code constructs introduced apply to other ITK iterators as well. This simple application crops a subregion from an image by copying its pixel values into to a second, smaller image.

We begin by including the appropriate header files.

```
#include "itkImageRegionConstIterator.h"
#include "itkImageRegionIterator.h"
```

Next we define a pixel type and corresponding image type. ITK iterator classes expect the image type as their template parameter.

```
const unsigned int Dimension = 2;

typedef unsigned char                    PixelType;
typedef otb::Image<PixelType, Dimension> ImageType;

typedef itk::ImageRegionConstIterator<ImageType> ConstIteratorType;
typedef itk::ImageRegionIterator<ImageType>      IteratorType;
```

Information about the subregion to copy is read from the command line. The subregion is defined by an `itk::ImageRegion` object, with a starting grid index and a size (Section 5.1).

```
ImageType::RegionType inputRegion;

ImageType::RegionType::IndexType inputStart;
ImageType::RegionType::SizeType  size;

inputStart[0] = ::atoi(argv[3]);
inputStart[1] = ::atoi(argv[4]);

size[0]  = ::atoi(argv[5]);
size[1]  = ::atoi(argv[6]);

inputRegion.SetSize(size);
inputRegion.SetIndex(inputStart);
```

The destination region in the output image is defined using the input region size, but a different start index. The starting index for the destination region is the corner of the newly generated image.

```
ImageType::RegionType outputRegion;

ImageType::RegionType::IndexType outputStart;

outputStart[0] = 0;
outputStart[1] = 0;

outputRegion.SetSize(size);
outputRegion.SetIndex(outputStart);
```

After reading the input image and checking that the desired subregion is, in fact, contained in the input, we allocate an output image. It is fundamental to set valid values to some of the basic image information during the copying process. In particular, the starting index of the output region is now filled up with zero values and the coordinates of the physical origin are computed as a shift from the origin of the input image. This is quite important since it will allow us to later register the extracted region against the original image.

```
ImageType::Pointer outputImage = ImageType::New();
outputImage->SetRegions(outputRegion);
const ImageType::SpacingType& spacing = reader->GetOutput()->GetSpacing();
const ImageType::PointType&   inputOrigin = reader->GetOutput()->GetOrigin();
double                        outputOrigin[Dimension];
```

```
for (unsigned int i = 0; i < Dimension; ++i)
  {
  outputOrigin[i] = inputOrigin[i] + spacing[i] * inputStart[i];
  }

outputImage->SetSpacing(spacing);
outputImage->SetOrigin(outputOrigin);
outputImage->Allocate();
```

The necessary images and region definitions are now in place. All that is left to do is to create the iterators and perform the copy. Note that image iterators are not accessed via smart pointers so they are light-weight objects that are instantiated on the stack. Also notice how the input and output iterators are defined over the *same corresponding region*. Though the images are different sizes, they both contain the same target subregion.

```
ConstIteratorType inputIt(reader->GetOutput(), inputRegion);
IteratorType      outputIt(outputImage,         outputRegion);

for (inputIt.GoToBegin(), outputIt.GoToBegin(); !inputIt.IsAtEnd();
     ++inputIt, ++outputIt)
  {
  outputIt.Set(inputIt.Get());
  }
```

The `for` loop above is a common construct in ITK/OTB. The beauty of these four lines of code is that they are equally valid for one, two, three, or even ten dimensional data, and no knowledge of the size of the image is necessary. Consider the ugly alternative of ten nested `for` loops for traversing an image.

Let's run this example on the image `QB_Suburb.png` found in `Examples/Data`. The command line arguments specify the input and output file names, then the x, y origin and the x, y size of the cropped subregion.

```
ImageRegionIterator QB_Suburb.png ImageRegionIteratorOutput.png 20 70 210 140
```

The output is the cropped subregion shown in Figure 25.2.

25.3.2 ImageRegionIteratorWithIndex

The source code for this example can be found in the file
`Examples/Iterators/ImageRegionIteratorWithIndex.cxx`.

The "WithIndex" family of iterators was designed for algorithms that use both the value and the location of image pixels in calculations. Unlike `itk::ImageRegionIterator`, which calculates an index only when asked for, `itk::ImageRegionIteratorWithIndex` maintains its index location

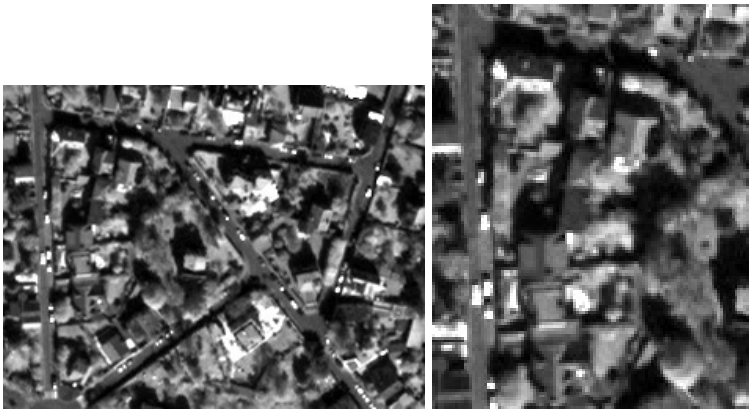


Figure 25.2: Cropping a region from an image. The original image is shown at left. The image on the right is the result of applying the ImageRegionIterator example code.

as a member variable that is updated during the increment or decrement process. Iteration speed is penalized, but the index queries are more efficient.

The following example illustrates the use of ImageRegionIteratorWithIndex. The algorithm mirrors a 2D image across its x-axis (see `itk::FlipImageFilter` for an ND version). The algorithm makes extensive use of the `GetIndex()` method.

We start by including the proper header file.

```
#include "itkImageRegionIteratorWithIndex.h"
```

For this example, we will use an RGB pixel type so that we can process color images. Like most other ITK image iterator, ImageRegionIteratorWithIndex class expects the image type as its single template parameter.

```
const unsigned int Dimension = 2;

typedef itk::RGBPixel<unsigned char>         RGBPixelType;
typedef otb::Image<RGBPixelType, Dimension> ImageType;

typedef itk::ImageRegionIteratorWithIndex<ImageType> IteratorType;
```

An `ImageType` smart pointer called `inputImage` points to the output of the image reader. After updating the image reader, we can allocate an output image of the same size, spacing, and origin as the input image.

```
ImageType::Pointer outputImage = ImageType::New();
outputImage->SetRegions(inputImage->GetRequestedRegion());
outputImage->CopyInformation(inputImage);
outputImage->Allocate();
```

Figure 25.3: Results of using ImageRegionIteratorWithIndex to mirror an image across an axis. The original image is shown at left. The mirrored output is shown at right.

Next we create the iterator that walks the output image. This algorithm requires no iterator for the input image.

```
IteratorType outputIt(outputImage, outputImage->GetRequestedRegion());
```

This axis flipping algorithm works by iterating through the output image, querying the iterator for its index, and copying the value from the input at an index mirrored across the x-axis.

```
ImageType::IndexType requestedIndex =
  outputImage->GetRequestedRegion().GetIndex();
ImageType::SizeType requestedSize =
  outputImage->GetRequestedRegion().GetSize();

for (outputIt.GoToBegin(); !outputIt.IsAtEnd(); ++outputIt)
  {
  ImageType::IndexType idx = outputIt.GetIndex();
  idx[0] =  requestedIndex[0] + requestedSize[0] - 1 - idx[0];
  outputIt.Set(inputImage->GetPixel(idx));
  }
```

Let's run this example on the image `ROI_QB_MUL_2.tif` found in the `Examples/Data` directory. Figure 25.3 shows how the original image has been mirrored across its x-axis in the output.

25.3.3 ImageLinearIteratorWithIndex

The source code for this example can be found in the file `Examples/Iterators/ImageLinearIteratorWithIndex.cxx`.

The `itk::ImageLinearIteratorWithIndex` is designed for line-by-line processing of an image. It walks a linear path along a selected image direction parallel to one of the coordinate axes of the image. This iterator conceptually breaks an image into a set of parallel lines that span the selected image dimension.

Like all image iterators, movement of the ImageLinearIteratorWithIndex is constrained within an image region R. The line ℓ through which the iterator moves is defined by selecting a direction and an origin. The line ℓ extends from the origin to the upper boundary of R. The origin can be moved to any position along the lower boundary of R.

Several additional methods are defined for this iterator to control movement of the iterator along the line ℓ and movement of the origin of ℓ.

- **`NextLine()`** Moves the iterator to the beginning pixel location of the next line in the image. The origin of the next line is determined by incrementing the current origin along the fastest increasing dimension of the subspace of the image that excludes the selected dimension.
- **`PreviousLine()`** Moves the iterator to the *last valid pixel location* in the previous line. The origin of the previous line is determined by decrementing the current origin along the fastest increasing dimension of the subspace of the image that excludes the selected dimension.
- **`GoToBeginOfLine()`** Moves the iterator to the beginning pixel of the current line.
- **`GoToEndOfLine()`** Move the iterator to *one past* the last valid pixel of the current line.
- **`IsAtReverseEndOfLine()`** Returns true if the iterator points to *one position before* the beginning pixel of the current line.
- **`IsAtEndOfLine()`** Returns true if the iterator points to *one position past* the last valid pixel of the current line.

The following code example shows how to use the ImageLinearIteratorWithIndex. It implements the same algorithm as in the previous example, flipping an image across its x-axis. Two line iterators are iterated in opposite directions across the x-axis. After each line is traversed, the iterator origins are stepped along the y-axis to the next line.

Headers for both the const and non-const versions are needed.

```
#include "itkImageLinearConstIteratorWithIndex.h"
#include "itkImageLinearIteratorWithIndex.h"
```

The RGB image and pixel types are defined as in the previous example. The ImageLinearIteratorWithIndex class and its const version each have single template parameters, the image type.

```
  typedef itk::ImageLinearIteratorWithIndex<ImageType>      IteratorType;
  typedef itk::ImageLinearConstIteratorWithIndex<ImageType> ConstIteratorType;
```

After reading the input image, we allocate an output image that of the same size, spacing, and origin.

```
  ImageType::Pointer outputImage = ImageType::New();
  outputImage->SetRegions(inputImage->GetRequestedRegion());
  outputImage->CopyInformation(inputImage);
  outputImage->Allocate();
```

Next we create the two iterators. The const iterator walks the input image, and the non-const iterator walks the output image. The iterators are initialized over the same region. The direction of iteration is set to 0, the x dimension.

```
ConstIteratorType inputIt(inputImage, inputImage->GetRequestedRegion());
IteratorType      outputIt(outputImage, inputImage->GetRequestedRegion());

inputIt.SetDirection(0);
outputIt.SetDirection(0);
```

Each line in the input is copied to the output. The input iterator moves forward across columns while the output iterator moves backwards.

```
for (inputIt.GoToBegin(),  outputIt.GoToBegin(); !inputIt.IsAtEnd();
     outputIt.NextLine(),  inputIt.NextLine())
  {
  inputIt.GoToBeginOfLine();
  outputIt.GoToEndOfLine();
  --outputIt;
  while (!inputIt.IsAtEndOfLine())
    {
    outputIt.Set(inputIt.Get());
    ++inputIt;
    --outputIt;
    }
  }
```

Running this example on `ROI_QB_MUL_1.tif` produces the same output image shown in Figure 25.3.

25.4 Neighborhood Iterators

In ITK, a pixel neighborhood is loosely defined as a small set of pixels that are locally adjacent to one another in an image. The size and shape of a neighborhood, as well the connectivity among pixels in a neighborhood, may vary with the application.

Many image processing algorithms are neighborhood-based, that is, the result at a pixel i is computed from the values of pixels in the ND neighborhood of i. Consider finite difference operations in 2D. A derivative at pixel index $i = (j,k)$, for example, is taken as a weighted difference of the values at $(j+1,k)$ and $(j-1,k)$. Other common examples of neighborhood operations include convolution filtering and image morphology.

This section describes a class of ITK image iterators that are designed for working with pixel neighborhoods. An ITK neighborhood iterator walks an image region just like a normal image iterator, but instead of only referencing a single pixel at each step, it simultaneously points to the entire ND neighborhood of pixels. Extensions to the standard iterator interface provide read and write access to all neighborhood pixels and information such as the size, extent, and location of the neighborhood.

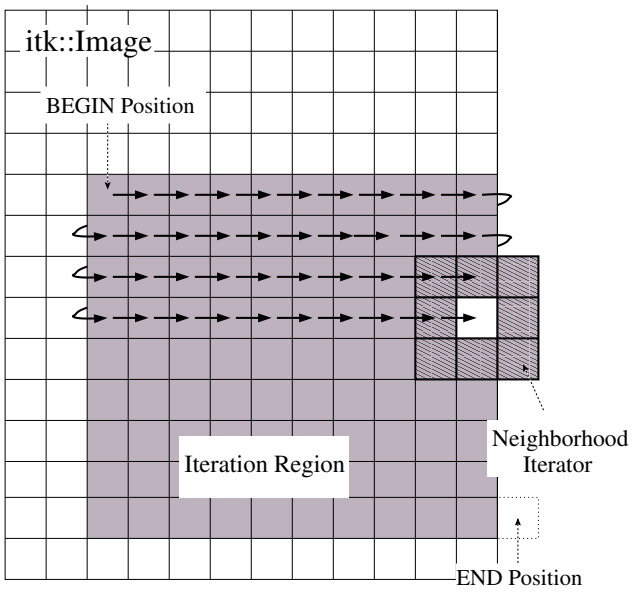


Figure 25.4: Path of a $3x3$ neighborhood iterator through a 2D image region. The extent of the neighborhood is indicated by the hashing around the iterator position. Pixels that lie within this extent are accessible through the iterator. An arrow denotes a single iterator step, the result of one ++ operation.

Neighborhood iterators use the same operators defined in Section 25.2 and the same code constructs as normal iterators for looping through an image. Figure 25.4 shows a neighborhood iterator moving through an iteration region. This iterator defines a $3x3$ neighborhood around each pixel that it visits. The *center* of the neighborhood iterator is always positioned over its current index and all other neighborhood pixel indices are referenced as offsets from the center index. The pixel under the center of the neighborhood iterator and all pixels under the shaded area, or *extent*, of the iterator can be dereferenced.

In addition to the standard image pointer and iteration region (Section 25.2), neighborhood iterator constructors require an argument that specifies the extent of the neighborhood to cover. Neighborhood extent is symmetric across its center in each axis and is given as an array of N distances that are collectively called the *radius*. Each element d of the radius, where $0 < d < N$ and N is the dimensionality of the neighborhood, gives the extent of the neighborhood in pixels for dimension N. The length of each face of the resulting ND hypercube is $2d+1$ pixels, a distance of d on either side of the single pixel at the neighbor center. Figure 25.5 shows the relationship between the radius of the iterator and the size of the neighborhood for a variety of 2D iterator shapes.

The radius of the neighborhood iterator is queried after construction by calling the `GetRadius()` method. Some other methods provide some useful information about the iterator and its underlying image.

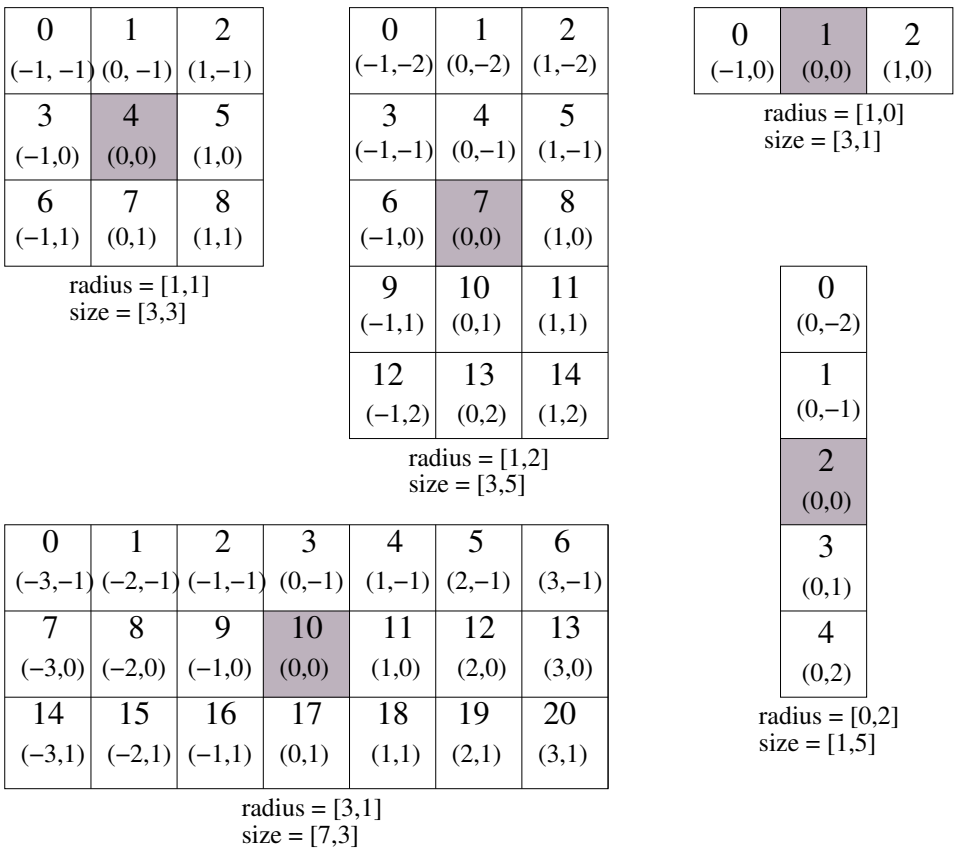


Figure 25.5: Several possible 2D neighborhood iterator shapes are shown along with their radii and sizes. A neighborhood pixel can be dereferenced by its integer index (top) or its offset from the center (bottom). The center pixel of each iterator is shaded.

- **`SizeType GetRadius()`** Returns the ND radius of the neighborhood as an `itk::Size`.
- **`const ImageType *GetImagePointer()`** Returns the pointer to the image referenced by the iterator.
- **`unsigned long Size()`** Returns the size in number of pixels of the neighborhood.

The neighborhood iterator interface extends the normal ITK iterator interface for setting and getting pixel values. One way to dereference pixels is to think of the neighborhood as a linear array where each pixel has a unique integer index. The index of a pixel in the array is determined by incrementing from the upper-left-forward corner of the neighborhood along the fastest increasing image dimension: first column, then row, then slice, and so on. In Figure 25.5, the unique integer index is shown at the top of each pixel. The center pixel is always at position $n/2$, where n is the size of the array.

- **`PixelType GetPixel(const unsigned int i)`** Returns the value of the pixel at neighborhood position `i`.
- **`void SetPixel(const unsigned int i, PixelType p)`** Sets the value of the pixel at position `i` to `p`.

Another way to think about a pixel location in a neighborhood is as an ND offset from the neighborhood center. The upper-left-forward corner of a $3x3x3$ neighborhood, for example, can be described by offset $(-1,-1,-1)$. The bottom-right-back corner of the same neighborhood is at offset $(1,1,1)$. In Figure 25.5, the offset from center is shown at the bottom of each neighborhood pixel.

- **`PixelType GetPixel(const OffsetType &o)`** Get the value of the pixel at the position offset `o` from the neighborhood center.
- **`void SetPixel(const OffsetType &o, PixelType p)`** Set the value at the position offset `o` from the neighborhood center to the value `p`.

The neighborhood iterators also provide a shorthand for setting and getting the value at the center of the neighborhood.

- **`PixelType GetCenterPixel()`** Gets the value at the center of the neighborhood.
- **`void SetCenterPixel(PixelType p)`** Sets the value at the center of the neighborhood to the value `p`

There is another shorthand for setting and getting values for pixels that lie some integer distance from the neighborhood center along one of the image axes.

- **PixelType GetNext(unsigned int d)** Get the value immediately adjacent to the neighborhood center in the positive direction along the d axis.
- **void SetNext(unsigned int d, PixelType p)** Set the value immediately adjacent to the neighborhood center in the positive direction along the d axis to the value p.
- **PixelType GetPrevious(unsigned int d)** Get the value immediately adjacent to the neighborhood center in the negative direction along the d axis.
- **void SetPrevious(unsigned int d, PixelType p)** Set the value immediately adjacent to the neighborhood center in the negative direction along the d axis to the value p.
- **PixelType GetNext(unsigned int d, unsigned int s)** Get the value of the pixel located s pixels from the neighborhood center in the positive direction along the d axis.
- **void SetNext(unsigned int d, unsigned int s, PixelType p)** Set the value of the pixel located s pixels from the neighborhood center in the positive direction along the d axis to value p.
- **PixelType GetPrevious(unsigned int d, unsigned int s)** Get the value of the pixel located s pixels from the neighborhood center in the positive direction along the d axis.
- **void SetPrevious(unsigned int d, unsigned int s, PixelType p)** Set the value of the pixel located s pixels from the neighborhood center in the positive direction along the d axis to value p.

It is also possible to extract or set all of the neighborhood values from an iterator at once using a regular ITK neighborhood object. This may be useful in algorithms that perform a particularly large number of calculations in the neighborhood and would otherwise require multiple dereferences of the same pixels.

- **NeighborhoodType GetNeighborhood()** Return a itk::Neighborhood of the same size and shape as the neighborhood iterator and contains all of the values at the iterator position.
- **void SetNeighborhood(NeighborhoodType &N)** Set all of the values in the neighborhood at the iterator position to those contained in Neighborhood N, which must be the same size and shape as the iterator.

Several methods are defined to provide information about the neighborhood.

- **IndexType GetIndex()** Return the image index of the center pixel of the neighborhood iterator.

- **`IndexType GetIndex(OffsetType o)`** Return the image index of the pixel at offset `o` from the neighborhood center.
- **`IndexType GetIndex(unsigned int i)`** Return the image index of the pixel at array position `i`.
- **`OffsetType GetOffset(unsigned int i)`** Return the offset from the neighborhood center of the pixel at array position `i`.
- **`unsigned long GetNeighborhoodIndex(OffsetType o)`** Return the array position of the pixel at offset `o` from the neighborhood center.
- **`std::slice GetSlice(unsigned int n)`** Return a `std::slice` through the iterator neighborhood along axis `n`.

A neighborhood-based calculation in a neighborhood close to an image boundary may require data that falls outside the boundary. The iterator in Figure 25.4, for example, is centered on a boundary pixel such that three of its neighbors actually do not exist in the image. When the extent of a neighborhood falls outside the image, pixel values for missing neighbors are supplied according to a rule, usually chosen to satisfy the numerical requirements of the algorithm. A rule for supplying out-of-bounds values is called a *boundary condition*.

ITK neighborhood iterators automatically detect out-of-bounds dereferences and will return values according to boundary conditions. The boundary condition type is specified by the second, optional template parameter of the iterator. By default, neighborhood iterators use a Neumann condition where the first derivative across the boundary is zero. The Neumann rule simply returns the closest in-bounds pixel value to the requested out-of-bounds location. Several other common boundary conditions can be found in the ITK toolkit. They include a periodic condition that returns the pixel value from the opposite side of the data set, and is useful when working with periodic data such as Fourier transforms, and a constant value condition that returns a set value v for all out-of-bounds pixel dereferences. The constant value condition is equivalent to padding the image with value v.

Bounds checking is a computationally expensive operation because it occurs each time the iterator is incremented. To increase efficiency, a neighborhood iterator automatically disables bounds checking when it detects that it is not necessary. A user may also explicitly disable or enable bounds checking. Most neighborhood based algorithms can minimize the need for bounds checking through clever definition of iteration regions. These techniques are explored in Section 25.4.1.

- **`void NeedToUseBoundaryConditionOn()`** Explicitly turn bounds checking on. This method should be used with caution because unnecessarily enabling bounds checking may result in a significant performance decrease. In general you should allow the iterator to automatically determine this setting.
- **`void NeedToUseBoundaryConditionOff()`** Explicitly disable bounds checking. This method should be used with caution because disabling bounds checking when it is needed will result in out-of-bounds reads and undefined results.

- **`void OverrideBoundaryCondition(BoundaryConditionType *b)`** Overrides the templated boundary condition, using boundary condition object `b` instead. Object `b` should not be deleted until it has been released by the iterator. This method can be used to change iterator behavior at run-time.
- **`void ResetBoundaryCondition()`** Discontinues the use of any run-time specified boundary condition and returns to using the condition specified in the template argument.
- **`void SetPixel(unsigned int i, PixelType p, bool status)`** Sets the value at neighborhood array position `i` to value `p`. If the position `i` is out-of-bounds, `status` is set to `false`, otherwise `status` is set to `true`.

The following sections describe the two ITK neighborhood iterator classes, `itk::NeighborhoodIterator` and `itk::ShapedNeighborhoodIterator`. Each has a const and a non-const version. The shaped iterator is a refinement of the standard NeighborhoodIterator that supports an arbitrarily-shaped (non-rectilinear) neighborhood.

25.4.1 NeighborhoodIterator

The standard neighborhood iterator class in ITK is the `itk::NeighborhoodIterator`. Together with its `const` version, `itk::ConstNeighborhoodIterator`, it implements the complete API described above. This section provides several examples to illustrate the use of NeighborhoodIterator.

Basic neighborhood techniques: edge detection

The source code for this example can be found in the file `Examples/Iterators/NeighborhoodIterators1.cxx`.

This example uses the `itk::NeighborhoodIterator` to implement a simple Sobel edge detection algorithm [50]. The algorithm uses the neighborhood iterator to iterate through an input image and calculate a series of finite difference derivatives. Since the derivative results cannot be written back to the input image without affecting later calculations, they are written instead to a second, output image. Most neighborhood processing algorithms follow this read-only model on their inputs.

We begin by including the proper header files. The `itk::ImageRegionIterator` will be used to write the results of computations to the output image. A const version of the neighborhood iterator is used because the input image is read-only.

```
#include "itkConstNeighborhoodIterator.h"
#include "itkImageRegionIterator.h"
```

The finite difference calculations in this algorithm require floating point values. Hence, we define the image pixel type to be `float` and the file reader will automatically cast fixed-point data to `float`.

We declare the iterator types using the image type as the template parameter. The second template parameter of the neighborhood iterator, which specifies the boundary condition, has been omitted because the default condition is appropriate for this algorithm.

```
typedef float                           PixelType;
typedef otb::Image<PixelType, 2>        ImageType;
typedef otb::ImageFileReader<ImageType> ReaderType;

typedef itk::ConstNeighborhoodIterator<ImageType> NeighborhoodIteratorType;
typedef itk::ImageRegionIterator<ImageType>       IteratorType;
```

The following code creates and executes the OTB image reader. The `Update` call on the reader object is surrounded by the standard `try/catch` blocks to handle any exceptions that may be thrown by the reader.

```
ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(argv[1]);
try
  {
  reader->Update();
  }
catch (itk::ExceptionObject& err)
  {
  std::cout << "ExceptionObject caught !" << std::endl;
  std::cout << err << std::endl;
  return -1;
  }
```

We can now create a neighborhood iterator to range over the output of the reader. For Sobel edge-detection in 2D, we need a square iterator that extends one pixel away from the neighborhood center in every dimension.

```
NeighborhoodIteratorType::RadiusType radius;
radius.Fill(1);
NeighborhoodIteratorType it(radius, reader->GetOutput(),
                            reader->GetOutput()->GetRequestedRegion());
```

The following code creates an output image and iterator.

```
ImageType::Pointer output = ImageType::New();
output->SetRegions(reader->GetOutput()->GetRequestedRegion());
output->Allocate();

IteratorType out(output, reader->GetOutput()->GetRequestedRegion());
```

Sobel edge detection uses weighted finite difference calculations to construct an edge magnitude image. Normally the edge magnitude is the root sum of squares of partial derivatives in all directions, but for simplicity this example only calculates the x component. The result is a derivative image biased toward maximally vertical edges.

The finite differences are computed from pixels at six locations in the neighborhood. In this example, we use the iterator `GetPixel()` method to query the values from their offsets in the neighborhood. The example in Section 25.4.1 uses convolution with a Sobel kernel instead.

Six positions in the neighborhood are necessary for the finite difference calculations. These positions are recorded in `offset1` through `offset6`.

```
NeighborhoodIteratorType::OffsetType offset1 = {{-1, -1}};
NeighborhoodIteratorType::OffsetType offset2 = {{1, -1}};
NeighborhoodIteratorType::OffsetType offset3 = {{-1, 0 }};
NeighborhoodIteratorType::OffsetType offset4 = {{1, 0}};
NeighborhoodIteratorType::OffsetType offset5 = {{-1, 1}};
NeighborhoodIteratorType::OffsetType offset6 = {{1, 1}};
```

It is equivalent to use the six corresponding integer array indices instead. For example, the offsets `(-1, -1)` and `(1, -1)` are equivalent to the integer indices `0` and `2`, respectively.

The calculations are done in a `for` loop that moves the input and output iterators synchronously across their respective images. The `sum` variable is used to sum the results of the finite differences.

```
for (it.GoToBegin(), out.GoToBegin(); !it.IsAtEnd(); ++it, ++out)
  {
  float sum;
  sum = it.GetPixel(offset2) - it.GetPixel(offset1);
  sum += 2.0 * it.GetPixel(offset4) - 2.0 * it.GetPixel(offset3);
  sum += it.GetPixel(offset6) - it.GetPixel(offset5);
  out.Set(sum);
  }
```

The last step is to write the output buffer to an image file. Writing is done inside a `try/catch` block to handle any exceptions. The output is rescaled to intensity range $[0, 255]$ and cast to unsigned char so that it can be saved and visualized as a PNG image.

```
typedef unsigned char                          WritePixelType;
typedef otb::Image<WritePixelType, 2>          WriteImageType;
typedef otb::ImageFileWriter<WriteImageType> WriterType;

typedef itk::RescaleIntensityImageFilter<
    ImageType, WriteImageType> RescaleFilterType;

RescaleFilterType::Pointer rescaler = RescaleFilterType::New();

rescaler->SetOutputMinimum(0);
rescaler->SetOutputMaximum(255);
rescaler->SetInput(output);

WriterType::Pointer writer = WriterType::New();
writer->SetFileName(argv[2]);
writer->SetInput(rescaler->GetOutput());
try
  {
  writer->Update();
  }
```

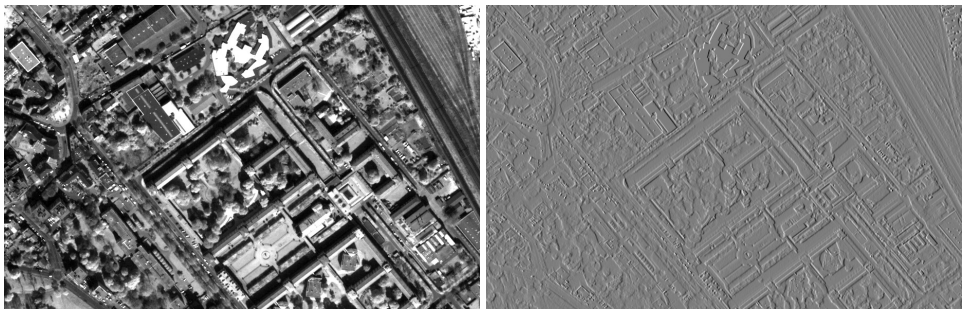


Figure 25.6: Applying the Sobel operator to an image (left) produces x (right) derivative image.

```
catch (itk::ExceptionObject& err)
  {
  std::cout << "ExceptionObject caught !" << std::endl;
  std::cout << err << std::endl;
  return -1;
  }
```

The center image of Figure 25.6 shows the output of the Sobel algorithm applied to `Examples/Data/ROI_QB_PAN_1.tif`.

Convolution filtering: Sobel operator

The source code for this example can be found in the file `Examples/Iterators/NeighborhoodIterators2.cxx`.

In this example, the Sobel edge-detection routine is rewritten using convolution filtering. Convolution filtering is a standard image processing technique that can be implemented numerically as the inner product of all image neighborhoods with a convolution kernel [50] [21]. In ITK, we use a class of objects called *neighborhood operators* as convolution kernels and a special function object called `itk::NeighborhoodInnerProduct` to calculate inner products.

The basic ITK convolution filtering routine is to step through the image with a neighborhood iterator and use NeighborhoodInnerProduct to find the inner product of each neighborhood with the desired kernel. The resulting values are written to an output image. This example uses a neighborhood operator called the `itk::SobelOperator`, but all neighborhood operators can be convolved with images using this basic routine. Other examples of neighborhood operators include derivative kernels, Gaussian kernels, and morphological operators. `itk::NeighborhoodOperatorImageFilter` is a generalization of the code in this section to ND images and arbitrary convolution kernels.

We start writing this example by including the header files for the Sobel kernel and the inner product function.

```
#include "itkSobelOperator.h"
```

```
#include "itkNeighborhoodInnerProduct.h"
```

Refer to the previous example for a description of reading the input image and setting up the output image and iterator.

The following code creates a Sobel operator. The Sobel operator requires a direction for its partial derivatives. This direction is read from the command line. Changing the direction of the derivatives changes the bias of the edge detection, i.e. maximally vertical or maximally horizontal.

```
itk::SobelOperator<PixelType, 2> sobelOperator;
sobelOperator.SetDirection(::atoi(argv[3]));
sobelOperator.CreateDirectional();
```

The neighborhood iterator is initialized as before, except that now it takes its radius directly from the radius of the Sobel operator. The inner product function object is templated over image type and requires no initialization.

```
NeighborhoodIteratorType::RadiusType radius = sobelOperator.GetRadius();
NeighborhoodIteratorType             it(radius, reader->GetOutput(),
                                        reader->GetOutput()->
                                        GetRequestedRegion());

itk::NeighborhoodInnerProduct<ImageType> innerProduct;
```

Using the Sobel operator, inner product, and neighborhood iterator objects, we can now write a very simple `for` loop for performing convolution filtering. As before, out-of-bounds pixel values are supplied automatically by the iterator.

```
for (it.GoToBegin(), out.GoToBegin(); !it.IsAtEnd(); ++it, ++out)
  {
  out.Set(innerProduct(it, sobelOperator));
  }
```

The output is rescaled and written as in the previous example. Applying this example in the x and y directions produces the images at the center and right of Figure 25.6. Note that x-direction operator produces the same output image as in the previous example.

Optimizing iteration speed

The source code for this example can be found in the file `Examples/Iterators/NeighborhoodIterators3.cxx`.

This example illustrates a technique for improving the efficiency of neighborhood calculations by eliminating unnecessary bounds checking. As described in Section 25.4, the neighborhood iterator automatically enables or disables bounds checking based on the iteration region in which it is initialized. By splitting our image into boundary and non-boundary regions, and then processing each region using a different neighborhood iterator, the algorithm will only perform bounds-checking on

those pixels for which it is actually required. This trick can provide a significant speedup for simple algorithms such as our Sobel edge detection, where iteration speed is a critical.

Splitting the image into the necessary regions is an easy task when you use the `itk::ImageBoundaryFacesCalculator`. The face calculator is so named because it returns a list of the "faces" of the ND dataset. Faces are those regions whose pixels all lie within a distance d from the boundary, where d is the radius of the neighborhood stencil used for the numerical calculations. In other words, faces are those regions where a neighborhood iterator of radius d will always overlap the boundary of the image. The face calculator also returns the single *inner* region, in which out-of-bounds values are never required and bounds checking is not necessary.

The face calculator object is defined in `itkNeighborhoodAlgorithm.h`. We include this file in addition to those from the previous two examples.

```
#include "itkNeighborhoodAlgorithm.h"
```

First we load the input image and create the output image and inner product function as in the previous examples. The image iterators will be created in a later step. Next we create a face calculator object. An empty list is created to hold the regions that will later on be returned by the face calculator.

```
typedef itk::NeighborhoodAlgorithm
::ImageBoundaryFacesCalculator<ImageType> FaceCalculatorType;

FaceCalculatorType               faceCalculator;
FaceCalculatorType::FaceListType faceList;
```

The face calculator function is invoked by passing it an image pointer, an image region, and a neighborhood radius. The image pointer is the same image used to initialize the neighborhood iterator, and the image region is the region that the algorithm is going to process. The radius is the radius of the iterator.

Notice that in this case the image region is given as the region of the *output* image and the image pointer is given as that of the *input* image. This is important if the input and output images differ in size, i.e. the input image is larger than the output image. ITK and OTB image filters, for example, operate on data from the input image but only generate results in the `RequestedRegion` of the output image, which may be smaller than the full extent of the input.

```
faceList = faceCalculator(reader->GetOutput(), output->GetRequestedRegion(),
                          sobelOperator.GetRadius());
```

The face calculator has returned a list of $2N + 1$ regions. The first element in the list is always the inner region, which may or may not be important depending on the application. For our purposes it does not matter because all regions are processed the same way. We use an iterator to traverse the list of faces.

```
FaceCalculatorType::FaceListType::iterator fit;
```

We now rewrite the main loop of the previous example so that each region in the list is processed by a separate iterator. The iterators `it` and `out` are reinitialized over each region in turn. Bounds checking is automatically enabled for those regions that require it, and disabled for the region that does not.

```
IteratorType             out;
NeighborhoodIteratorType it;

for (fit = faceList.begin(); fit != faceList.end(); ++fit)
  {
  it = NeighborhoodIteratorType(sobelOperator.GetRadius(),
                                reader->GetOutput(), *fit);
  out = IteratorType(output, *fit);

  for (it.GoToBegin(), out.GoToBegin(); !it.IsAtEnd(); ++it, ++out)
    {
    out.Set(innerProduct(it, sobelOperator));
    }
  }
```

The output is written as before. Results for this example are the same as the previous example. You may not notice the speedup except on larger images. When moving to 3D and higher dimensions, the effects are greater because the volume to surface area ratio is usually larger. In other words, as the number of interior pixels increases relative to the number of face pixels, there is a corresponding increase in efficiency from disabling bounds checking on interior pixels.

Separable convolution: Gaussian filtering

The source code for this example can be found in the file `Examples/Iterators/NeighborhoodIterators4.cxx`.

We now introduce a variation on convolution filtering that is useful when a convolution kernel is separable. In this example, we create a different neighborhood iterator for each axial direction of the image and then take separate inner products with a 1D discrete Gaussian kernel. The idea of using several neighborhood iterators at once has applications beyond convolution filtering and may improve efficiency when the size of the whole neighborhood relative to the portion of the neighborhood used in calculations becomes large.

The only new class necessary for this example is the Gaussian operator.

```
#include "itkGaussianOperator.h"
```

The Gaussian operator, like the Sobel operator, is instantiated with a pixel type and a dimensionality. Additionally, we set the variance of the Gaussian, which has been read from the command line as standard deviation.

```
itk::GaussianOperator<PixelType, 2> gaussianOperator;
gaussianOperator.SetVariance(::atof(argv[3]) * ::atof(argv[3]));
```

The only further changes from the previous example are in the main loop. Once again we use the results from face calculator to construct a loop that processes boundary and non-boundary image regions separately. Separable convolution, however, requires an additional, outer loop over all the image dimensions. The direction of the Gaussian operator is reset at each iteration of the outer loop using the new dimension. The iterators change direction to match because they are initialized with the radius of the Gaussian operator.

Input and output buffers are swapped at each iteration so that the output of the previous iteration becomes the input for the current iteration. The swap is not performed on the last iteration.

```
ImageType::Pointer input = reader->GetOutput();
for (unsigned int i = 0; i < ImageType::ImageDimension; ++i)
  {
  gaussianOperator.SetDirection(i);
  gaussianOperator.CreateDirectional();

  faceList = faceCalculator(input, output->GetRequestedRegion(),
                            gaussianOperator.GetRadius());

  for (fit = faceList.begin(); fit != faceList.end(); ++fit)
    {
    it = NeighborhoodIteratorType(gaussianOperator.GetRadius(),
                                  input, *fit);

    out = IteratorType(output, *fit);

    for (it.GoToBegin(), out.GoToBegin(); !it.IsAtEnd(); ++it, ++out)
      {
      out.Set(innerProduct(it, gaussianOperator));
      }
    }

  // Swap the input and output buffers
  if (i != ImageType::ImageDimension - 1)
    {
    ImageType::Pointer tmp = input;
    input = output;
    output = tmp;
    }
  }
```

The output is rescaled and written as in the previous examples. Figure 25.7 shows the results of Gaussian blurring the image `Examples/Data/QB_Suburb.png` using increasing kernel widths.

Random access iteration

The source code for this example can be found in the file `Examples/Iterators/NeighborhoodIterators6.cxx`.

Some image processing routines do not need to visit every pixel in an image. Flood-fill and

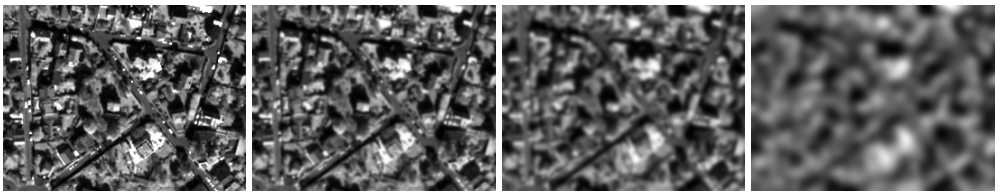


Figure 25.7: Results of convolution filtering with a Gaussian kernel of increasing standard deviation σ (from left to right, $\sigma = 0$, $\sigma = 1$, $\sigma = 2$, $\sigma = 5$). Increased blurring reduces contrast and changes the average intensity value of the image, which causes the image to appear brighter when rescaled.

connected-component algorithms, for example, only visit pixels that are locally connected to one another. Algorithms such as these can be efficiently written using the random access capabilities of the neighborhood iterator.

The following example finds local minima. Given a seed point, we can search the neighborhood of that point and pick the smallest value m. While m is not at the center of our current neighborhood, we move in the direction of m and repeat the analysis. Eventually we discover a local minimum and stop. This algorithm is made trivially simple in ND using an ITK neighborhood iterator.

To illustrate the process, we create an image that descends everywhere to a single minimum: a positive distance transform to a point. The details of creating the distance transform are not relevant to the discussion of neighborhood iterators, but can be found in the source code of this example. Some noise has been added to the distance transform image for additional interest.

The variable `input` is the pointer to the distance transform image. The local minimum algorithm is initialized with a seed point read from the command line.

```
ImageType::IndexType index;
index[0] = ::atoi(argv[2]);
index[1] = ::atoi(argv[3]);
```

Next we create the neighborhood iterator and position it at the seed point.

```
NeighborhoodIteratorType::RadiusType radius;
radius.Fill(1);
NeighborhoodIteratorType it(radius, input, input->GetRequestedRegion());

it.SetLocation(index);
```

Searching for the local minimum involves finding the minimum in the current neighborhood, then shifting the neighborhood in the direction of that minimum. The `for` loop below records the `itk::Offset` of the minimum neighborhood pixel. The neighborhood iterator is then moved using that offset. When a local minimum is detected, `flag` will remain false and the `while` loop will exit. Note that this code is valid for an image of any dimensionality.

```
bool flag = true;
while (flag == true)
```

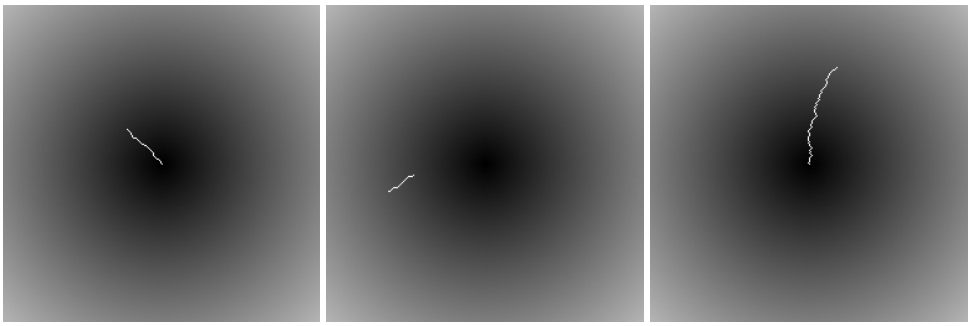


Figure 25.8: Paths traversed by the neighborhood iterator from different seed points to the local minimum. The true minimum is at the center of the image. The path of the iterator is shown in white. The effect of noise in the image is seen as small perturbations in each path.

```
{
NeighborhoodIteratorType::OffsetType nextMove;
nextMove.Fill(0);

flag = false;

PixelType min = it.GetCenterPixel();
for (unsigned i = 0; i < it.Size(); ++i)
  {
  if (it.GetPixel(i) < min)
    {
    min = it.GetPixel(i);
    nextMove = it.GetOffset(i);
    flag = true;
    }
  }
it.SetCenterPixel(255.0);
it += nextMove;
}
```

Figure 25.8 shows the results of the algorithm for several seed points. The white line is the path of the iterator from the seed point to the minimum in the center of the image. The effect of the additive noise is visible as the small perturbations in the paths.

25.4.2 ShapedNeighborhoodIterator

This section describes a variation on the neighborhood iterator called a *shaped* neighborhood iterator. A shaped neighborhood is defined like a bit mask, or *stencil*, with different offsets in the rectilinear neighborhood of the normal neighborhood iterator turned off or on to create a pattern. Inactive positions (those not in the stencil) are not updated during iteration and their values cannot be read or written. The shaped iterator is implemented in the class

`itk::ShapedNeighborhoodIterator`, which is a subclass of `itk::NeighborhoodIterator`. A const version, `itk::ConstShapedNeighborhoodIterator`, is also available.

Like a regular neighborhood iterator, a shaped neighborhood iterator must be initialized with an ND radius object, but the radius of the neighborhood of a shaped iterator only defines the set of *possible* neighbors. Any number of possible neighbors can then be activated or deactivated. The shaped neighborhood iterator defines an API for activating neighbors. When a neighbor location, defined relative to the center of the neighborhood, is activated, it is placed on the *active list* and is then part of the stencil. An iterator can be "reshaped" at any time by adding or removing offsets from the active list.

- **`void ActivateOffset(OffsetType &o)`** Include the offset `o` in the stencil of active neighborhood positions. Offsets are relative to the neighborhood center.
- **`void DeactivateOffset(OffsetType &o)`** Remove the offset `o` from the stencil of active neighborhood positions. Offsets are relative to the neighborhood center.
- **`void ClearActiveList()`** Deactivate all positions in the iterator stencil by clearing the active list.
- **`unsigned int GetActiveIndexListSize()`** Return the number of pixel locations that are currently active in the shaped iterator stencil.

Because the neighborhood is less rigidly defined in the shaped iterator, the set of pixel access methods is restricted. Only the `GetPixel()` and `SetPixel()` methods are available, and calling these methods on an inactive neighborhood offset will return undefined results.

For the common case of traversing all pixel offsets in a neighborhood, the shaped iterator class provides an iterator through the active offsets in its stencil. This *stencil iterator* can be incremented or decremented and defines `Get()` and `Set()` for reading and writing the values in the neighborhood.

- **`ShapedNeighborhoodIterator::Iterator Begin()`** Return a const or non-const iterator through the shaped iterator stencil that points to the first valid location in the stencil.
- **`ShapedNeighborhoodIterator::Iterator End()`** Return a const or non-const iterator through the shaped iterator stencil that points *one position past* the last valid location in the stencil.

The functionality and interface of the shaped neighborhood iterator is best described by example. We will use the ShapedNeighborhoodIterator to implement some binary image morphology algorithms (see [50], [21], et al.). The examples that follow implement erosion and dilation.

Shaped neighborhoods: morphological operations

The source code for this example can be found in the file
`Examples/Iterators/ShapedNeighborhoodIterators1.cxx`.

This example uses `itk::ShapedNeighborhoodIterator` to implement a binary erosion algorithm. If we think of an image I as a set of pixel indices, then erosion of I by a smaller set E, called the *structuring element*, is the set of all indices at locations x in I such that when E is positioned at x, every element in E is also contained in I.

This type of algorithm is easy to implement with shaped neighborhood iterators because we can use the iterator itself as the structuring element E and move it sequentially through all positions x. The result at x is obtained by checking values in a simple iteration loop through the neighborhood stencil.

We need two iterators, a shaped iterator for the input image and a regular image iterator for writing results to the output image.

```
#include "itkConstShapedNeighborhoodIterator.h"
#include "itkImageRegionIterator.h"
```

Since we are working with binary images in this example, an `unsigned char` pixel type will do. The image and iterator types are defined using the pixel type.

```
typedef unsigned char            PixelType;
typedef otb::Image<PixelType, 2> ImageType;

typedef itk::ConstShapedNeighborhoodIterator<
    ImageType
    > ShapedNeighborhoodIteratorType;

typedef itk::ImageRegionIterator<ImageType> IteratorType;
```

Refer to the examples in Section 25.4.1 or the source code of this example for a description of how to read the input image and allocate a matching output image.

The size of the structuring element is read from the command line and used to define a radius for the shaped neighborhood iterator. Using the method developed in section 25.4.1 to minimize bounds checking, the iterator itself is not initialized until entering the main processing loop.

```
unsigned int                                element_radius = ::atoi(argv[3]);
ShapedNeighborhoodIteratorType::RadiusType radius;
radius.Fill(element_radius);
```

The face calculator object introduced in Section 25.4.1 is created and used as before.

```
typedef itk::NeighborhoodAlgorithm::ImageBoundaryFacesCalculator<
    ImageType> FaceCalculatorType;

FaceCalculatorType                          faceCalculator;
FaceCalculatorType::FaceListType            faceList;
FaceCalculatorType::FaceListType::iterator fit;
```

```
faceList = faceCalculator(reader->GetOutput(),
                          output->GetRequestedRegion(),
                          radius);
```

Now we initialize some variables and constants.

```
IteratorType out;

const PixelType background_value = 0;
const PixelType foreground_value = 255;
const float     rad = static_cast<float>(element_radius);
```

The outer loop of the algorithm is structured as in previous neighborhood iterator examples. Each region in the face list is processed in turn. As each new region is processed, the input and output iterators are initialized on that region.

The shaped iterator that ranges over the input is our structuring element and its active stencil must be created accordingly. For this example, the structuring element is shaped like a circle of radius `element_radius`. Each of the appropriate neighborhood offsets is activated in the double `for` loop.

```
for (fit = faceList.begin(); fit != faceList.end(); ++fit)
  {
  ShapedNeighborhoodIteratorType it(radius, reader->GetOutput(), *fit);
  out = IteratorType(output, *fit);

  // Creates a circular structuring element by activating all the pixels less
  // than radius distance from the center of the neighborhood.

  for (float y = -rad; y <= rad; y++)
    {
    for (float x = -rad; x <= rad; x++)
      {
      ShapedNeighborhoodIteratorType::OffsetType off;

      float dis = ::sqrt(x * x + y * y);
      if (dis <= rad)
        {
        off[0] = static_cast<int>(x);
        off[1] = static_cast<int>(y);
        it.ActivateOffset(off);
        }
      }
    }
```

The inner loop, which implements the erosion algorithm, is fairly simple. The `for` loop steps the input and output iterators through their respective images. At each step, the active stencil of the shaped iterator is traversed to determine whether all pixels underneath the stencil contain the foreground value, i.e. are contained within the set I. Note the use of the stencil iterator, `ci`, in performing this check.

```
  // Implements erosion
  for (it.GoToBegin(), out.GoToBegin(); !it.IsAtEnd(); ++it, ++out)
    {
    ShapedNeighborhoodIteratorType::ConstIterator ci;

    bool flag = true;
    for (ci = it.Begin(); ci != it.End(); ci++)
      {
      if (ci.Get() == background_value)
        {
        flag = false;
        break;
        }
      }
    if (flag == true)
      {
      out.Set(foreground_value);
      }
    else
      {
      out.Set(background_value);
      }
    }
  }
```

The source code for this example can be found in the file `Examples/Iterators/ShapedNeighborhoodIterators2.cxx`.

The logic of the inner loop can be rewritten to perform dilation. Dilation of the set I by E is the set of all x such that E positioned at x contains at least one element in I.

```
  // Implements dilation
  for (it.GoToBegin(), out.GoToBegin(); !it.IsAtEnd(); ++it, ++out)
    {
    ShapedNeighborhoodIteratorType::ConstIterator ci;

    bool flag = false;
    for (ci = it.Begin(); ci != it.End(); ci++)
      {
      if (ci.Get() != background_value)
        {
        flag = true;
        break;
        }
      }
    if (flag == true)
      {
      out.Set(foreground_value);
      }
    else
      {
      out.Set(background_value);
      }
    }
```

Figure 25.9: The effects of morphological operations on a binary image using a circular structuring element of size 4. Left: original image. Right: dilation.

```
    }
```

The output image is written and visualized directly as a binary image of `unsigned chars`. Figure 25.9 illustrates the results of dilation on the image `Examples/Data/BinaryImage.png`. Applying erosion and dilation in sequence effects the morphological operations of opening and closing.

CHAPTER

TWENTYSIX

IMAGE ADAPTORS

The purpose of an *image adaptor* is to make one image appear like another image, possibly of a different pixel type. A typical example is to take an image of pixel type `unsigned char` and present it as an image of pixel type `float`. The motivation for using image adaptors in this case is to avoid the extra memory resources required by using a casting filter. When we use the `itk::CastImageFilter` for the conversion, the filter creates a memory buffer large enough to store the `float` image. The `float` image requires four times the memory of the original image and contains no useful additional information. Image adaptors, on the other hand, do not require the extra memory as pixels are converted only when they are read using image iterators (see Chapter 25).

Image adaptors are particularly useful when there is infrequent pixel access, since the actual conversion occurs on the fly during the access operation. In such cases the use of image adaptors may reduce overall computation time as well as reduce memory usage. The use of image adaptors, however, can be disadvantageous in some situations. For example, when the downstream filter is executed multiple times, a CastImageFilter will cache its output after the first execution and will not re-execute when the filter downstream is updated. Conversely, an image adaptor will compute the cast every time.

Another application for image adaptors is to perform lightweight pixel-wise operations replacing the need for a filter. In the toolkit, adaptors are defined for many single valued and single parameter functions such as trigonometric, exponential and logarithmic functions. For example,

- `itk::ExpImageAdaptor`
- `itk::SinImageAdaptor`
- `itk::CosImageAdaptor`

The following examples illustrate common applications of image adaptors.

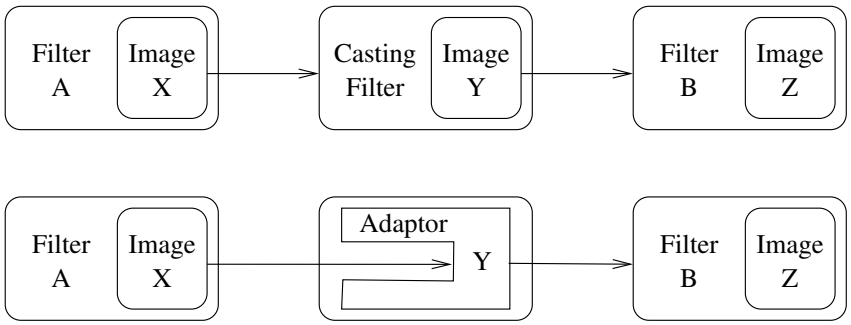


Figure 26.1: The difference between using a CastImageFilter and an ImageAdaptor. ImageAdaptors convert pixel values when they are accessed by iterators. Thus, they do not produces an intermediate image. In the example illustrated by this figure, the *Image Y* is not created by the ImageAdaptor; instead, the image is simulated on the fly each time an iterator from the filter downstream attempts to access the image data.

26.1 Image Casting

The source code for this example can be found in the file
`Examples/DataRepresentation/Image/ImageAdaptor1.cxx`.

This example illustrates how the `itk::ImageAdaptor` can be used to cast an image from one pixel type to another. In particular, we will *adapt* an `unsigned char` image to make it appear as an image of pixel type `float`.

We begin by including the relevant headers.

```
#include "otbImage.h"
#include "itkImageAdaptor.h"
```

First, we need to define a *pixel accessor* class that does the actual conversion. Note that in general, the only valid operations for pixel accessors are those that only require the value of the input pixel. As such, neighborhood type operations are not possible. A pixel accessor must provide methods `Set()` and `Get()`, and define the types of `InternalPixelType` and `ExternalPixelType`. The `InternalPixelType` corresponds to the pixel type of the image to be adapted (`unsigned char` in this example). The `ExternalPixelType` corresponds to the pixel type we wish to emulate with the ImageAdaptor (`float` in this case).

```
class CastPixelAccessor
{
public:
  typedef unsigned char InternalType;
  typedef float         ExternalType;

  static void Set(InternalType& output, const ExternalType& input)
  {
    output = static_cast<InternalType>(input);
```

```
  }

  static ExternalType Get(const InternalType& input)
  {
    return static_cast<ExternalType>(input);
  }
};
```

The CastPixelAccessor class simply applies a `static_cast` to the pixel values. We now use this pixel accessor to define the image adaptor type and create an instance using the standard `New()` method.

```
  typedef unsigned char InputPixelType;
  const unsigned int Dimension = 2;
  typedef otb::Image<InputPixelType, Dimension> ImageType;

  typedef itk::ImageAdaptor<ImageType, CastPixelAccessor> ImageAdaptorType;
  ImageAdaptorType::Pointer adaptor = ImageAdaptorType::New();
```

We also create an image reader templated over the input image type and read the input image from file.

```
  typedef otb::ImageFileReader<ImageType> ReaderType;
  ReaderType::Pointer reader = ReaderType::New();
```

The output of the reader is then connected as the input to the image adaptor.

```
  adaptor->SetImage(reader->GetOutput());
```

In the following code, we visit the image using an iterator instantiated using the adapted image type and compute the sum of the pixel values.

```
  typedef itk::ImageRegionIteratorWithIndex<ImageAdaptorType> IteratorType;
  IteratorType it(adaptor, adaptor->GetBufferedRegion());

  double sum = 0.0;
  it.GoToBegin();
  while (!it.IsAtEnd())
    {
    float value = it.Get();
    sum += value;
    ++it;
    }
```

Although in this example, we are just performing a simple summation, the key concept is that access to pixels is performed as if the pixel is of type `float`. Additionally, it should be noted that the adaptor is used as if it was an actual image and not as a filter. ImageAdaptors conform to the same API as the `otb::Image` class.

26.2 Adapting RGB Images

The source code for this example can be found in the file
`Examples/DataRepresentation/Image/ImageAdaptor2.cxx`.

This example illustrates how to use the `itk::ImageAdaptor` to access the individual components of an RGB image. In this case, we create an ImageAdaptor that will accept a RGB image as input and presents it as a scalar image. The pixel data will be taken directly from the red channel of the original image.

As with the previous example, the bulk of the effort in creating the image adaptor is associated with the definition of the pixel accessor class. In this case, the accessor converts a RGB vector to a scalar containing the red channel component. Note that in the following, we do not need to define the `Set()` method since we only expect the adaptor to be used for reading data from the image.

```
class RedChannelPixelAccessor
{
public:
  typedef itk::RGBPixel<float> InternalType;
  typedef               float  ExternalType;

  static ExternalType Get(const InternalType& input)
  {
    return static_cast<ExternalType>(input.GetRed());
  }
};
```

The `Get()` method simply calls the `GetRed()` method defined in the `itk::RGBPixel` class.

Now we use the internal pixel type of the pixel accessor to define the input image type, and then proceed to instantiate the ImageAdaptor type.

```
  typedef RedChannelPixelAccessor::InternalType InputPixelType;
  const unsigned int Dimension = 2;
  typedef otb::Image<InputPixelType, Dimension> ImageType;

  typedef itk::ImageAdaptor<ImageType,
      RedChannelPixelAccessor> ImageAdaptorType;

  ImageAdaptorType::Pointer adaptor = ImageAdaptorType::New();
```

We create an image reader and connect the output to the adaptor as before.

```
  typedef otb::ImageFileReader<ImageType> ReaderType;
  ReaderType::Pointer reader = ReaderType::New();
```

```
  adaptor->SetImage(reader->GetOutput());
```

We create an `itk::RescaleIntensityImageFilter` and an `otb::ImageFileWriter` to rescale the dynamic range of the pixel values and send the extracted channel to an image file. Note that the

image type used for the rescaling filter is the `ImageAdaptorType` itself. That is, the adaptor type is used in the same context as an image type.

```
  typedef otb::Image<unsigned char, Dimension> OutputImageType;
  typedef itk::RescaleIntensityImageFilter<ImageAdaptorType,
      OutputImageType
      >   RescalerType;

  RescalerType::Pointer rescaler = RescalerType::New();
  typedef otb::ImageFileWriter<OutputImageType> WriterType;
  WriterType::Pointer writer = WriterType::New();
```

Now we connect the adaptor as the input to the rescaler and set the parameters for the intensity rescaling.

```
  rescaler->SetOutputMinimum(0);
  rescaler->SetOutputMaximum(255);

  rescaler->SetInput(adaptor);
  writer->SetInput(rescaler->GetOutput());
```

Finally, we invoke the `Update()` method on the writer and take precautions to catch any exception that may be thrown during the execution of the pipeline.

```
  try
    {
    writer->Update();
    }
  catch (itk::ExceptionObject& excp)
    {
    std::cerr << "Exception caught " << excp << std::endl;
    return 1;
    }
```

ImageAdaptors for the green and blue channels can easily be implemented by modifying the pixel accessor of the red channel and then using the new pixel accessor for instantiating the type of an image adaptor. The following define a green channel pixel accessor.

```
  class GreenChannelPixelAccessor
  {
public:
    typedef itk::RGBPixel<float> InternalType;
    typedef               float  ExternalType;

    static ExternalType Get(const InternalType& input)
    {
      return static_cast<ExternalType>(input.GetGreen());
    }
  };
```

A blue channel pixel accessor is similarly defined.

```
  class BlueChannelPixelAccessor
  {
public:
    typedef itk::RGBPixel<float> InternalType;
    typedef               float  ExternalType;

    static ExternalType Get(const InternalType& input)
    {
      return static_cast<ExternalType>(input.GetBlue());
    }
  };
```

26.3 Adapting Vector Images

The source code for this example can be found in the file
`Examples/DataRepresentation/Image/ImageAdaptor3.cxx`.

This example illustrates the use of `itk::ImageAdaptor` to obtain access to the components of a vector image. Specifically, it shows how to manage pixel accessors containing internal parameters. In this example we create an image of vectors by using a gradient filter. Then, we use an image adaptor to extract one of the components of the vector image. The vector type used by the gradient filter is the `itk::CovariantVector` class.

We start by including the relevant headers.

```
#include "itkCovariantVector.h"
#include "itkGradientRecursiveGaussianImageFilter.h"
```

A pixel accessors class may have internal parameters that affect the operations performed on input pixel data. Image adaptors support parameters in their internal pixel accessor by using the assignment operator. Any pixel accessor which has internal parameters must therefore implement the assignment operator. The following defines a pixel accessor for extracting components from a vector pixel. The `m_Index` member variable is used to select the vector component to be returned.

```
class VectorPixelAccessor
{
public:
  typedef itk::CovariantVector<float, 2> InternalType;
  typedef                      float     ExternalType;

  void operator =(const VectorPixelAccessor& vpa)
  {
    m_Index = vpa.m_Index;
  }
  ExternalType Get(const InternalType& input) const
  {
    return static_cast<ExternalType>(input[m_Index]);
  }
```

```
  void SetIndex(unsigned int index)
  {
    m_Index = index;
  }
private:
  unsigned int m_Index;
};
```

The `Get()` method simply returns the *i*-th component of the vector as indicated by the index. The assignment operator transfers the value of the index member variable from one instance of the pixel accessor to another.

In order to test the pixel accessor, we generate an image of vectors using the `itk::GradientRecursiveGaussianImageFilter`. This filter produces an output image of `itk::CovariantVector` pixel type. Covariant vectors are the natural representation for gradients since they are the equivalent of normals to iso-values manifolds.

```
  typedef unsigned char InputPixelType;
  const unsigned int Dimension = 2;
  typedef otb::Image<InputPixelType,  Dimension> InputImageType;
  typedef itk::CovariantVector<float, Dimension> VectorPixelType;
  typedef otb::Image<VectorPixelType, Dimension> VectorImageType;
  typedef itk::GradientRecursiveGaussianImageFilter<InputImageType,
      VectorImageType>
  GradientFilterType;

  GradientFilterType::Pointer gradient = GradientFilterType::New();
```

We instantiate the ImageAdaptor using the vector image type as the first template parameter and the pixel accessor as the second template parameter.

```
  typedef itk::ImageAdaptor<VectorImageType,
      VectorPixelAccessor> ImageAdaptorType;

  ImageAdaptorType::Pointer adaptor = ImageAdaptorType::New();
```

The index of the component to be extracted is specified from the command line. In the following, we create the accessor, set the index and connect the accessor to the image adaptor using the `SetPixelAccessor()` method.

```
  VectorPixelAccessor accessor;
  accessor.SetIndex(atoi(argv[3]));
  adaptor->SetPixelAccessor(accessor);
```

We create a reader to load the image specified from the command line and pass its output as the input to the gradient filter.

```
  typedef otb::ImageFileReader<InputImageType> ReaderType;
  ReaderType::Pointer reader = ReaderType::New();
  gradient->SetInput(reader->GetOutput());
```

```
  reader->SetFileName(argv[1]);
  gradient->Update();
```

We now connect the output of the gradient filter as input to the image adaptor. The adaptor emulates a scalar image whose pixel values are taken from the selected component of the vector image.

```
  adaptor->SetImage(gradient->GetOutput());
```

26.4 Adaptors for Simple Computation

The source code for this example can be found in the file `Examples/DataRepresentation/Image/ImageAdaptor4.cxx`.

Image adaptors can also be used to perform simple pixel-wise computations on image data. The following example illustrates how to use the `itk::ImageAdaptor` for image thresholding.

A pixel accessor for image thresholding requires that the accessor maintain the threshold value. Therefore, it must also implement the assignment operator to set this internal parameter.

```
class ThresholdingPixelAccessor
{
public:
  typedef unsigned char InternalType;
  typedef unsigned char ExternalType;

  ExternalType Get(const InternalType& input) const
  {
    return (input > m_Threshold) ? 1 : 0;
  }
  void SetThreshold(const InternalType threshold)
  {
    m_Threshold = threshold;
  }

  void operator =(const ThresholdingPixelAccessor& vpa)
  {
    m_Threshold = vpa.m_Threshold;
  }
private:
  InternalType m_Threshold;
};
```

The `Get()` method returns one if the input pixel is above the threshold and zero otherwise. The assignment operator transfers the value of the threshold member variable from one instance of the pixel accessor to another.

To create an image adaptor, we first instantiate an image type whose pixel type is the same as the internal pixel type of the pixel accessor.

Figure 26.2: Using ImageAdaptor to perform a simple image computation. An ImageAdaptor is used to perform binary thresholding on the input image on the left. The center image was created using a threshold of 100, while the image on the right corresponds to a threshold of 200.

```
typedef ThresholdingPixelAccessor::InternalType PixelType;
const unsigned int Dimension = 2;
typedef otb::Image<PixelType,  Dimension> ImageType;
```

We instantiate the ImageAdaptor using the image type as the first template parameter and the pixel accessor as the second template parameter.

```
typedef itk::ImageAdaptor<ImageType,
    ThresholdingPixelAccessor> ImageAdaptorType;

ImageAdaptorType::Pointer adaptor = ImageAdaptorType::New();
```

The threshold value is set from the command line. A threshold pixel accessor is created and connected to the image adaptor in the same manner as in the previous example.

```
ThresholdingPixelAccessor accessor;
accessor.SetThreshold(atoi(argv[3]));
adaptor->SetPixelAccessor(accessor);
```

We create a reader to load the input image and connect the output of the reader as the input to the adaptor.

```
typedef otb::ImageFileReader<ImageType> ReaderType;
ReaderType::Pointer reader = ReaderType::New();
reader->SetFileName(argv[1]);
reader->Update();

adaptor->SetImage(reader->GetOutput());
```

As before, we rescale the emulated scalar image before writing it out to file. Figure 26.2 illustrates the result of applying the thresholding adaptor to a typical gray scale image using two different threshold values. Note that the same effect could have been achieved by using the `itk::BinaryThresholdImageFilter` but at the price of holding an extra copy of the image in memory.

26.5 Adaptors and Writers

Image adaptors will not behave correctly when connected directly to a writer. The reason is that writers tend to get direct access to the image buffer from their input, since image adaptors do not have a real buffer their behavior in this circumstances is incorrect. You should avoid instantiating the `ImageFileWriter` or the `ImageSeriesWriter` over an image adaptor type.

CHAPTER

TWENTYSEVEN

STREAMING AND THREADING

Streaming and threading are a complex issue in computing in general. This chapter provides the keys to help you understand how it is working so you can make the right choices later.

27.1 Introduction

First, you have to be aware that streaming and threading are two different things even if they are linked to a certain extent. In OTB:

- Streaming describes the ability to combine the processing of several portion of a big image and to make the output identical as what you would have got if the whole image was processed at once. Streaming is compulsory when you're processing gigabyte images.
- Threading is the ability to process simultaneously different parts of the image. Threading will give you some benefits only if you have a fairly recent processor (dual, quad core and some older P4).

To sum up: streaming is good if you have big images, threading is good if you have several processing units.

However, these two properties are not unrelated. Both rely on the filter ability to process parts of the image and combine the result, that what the ThreadedGenerateData() method can do.

27.2 Streaming and threading in OTB

For OTB, streaming is pipeline related while threading is filter related. If you build a pipeline where one filter is not streamable, the whole pipeline is not streamable: at one point, you would hold the entire image in memory. Whereas you will benefit from a threaded filter even if the rest of

the pipeline is made of non-threadable filters (the processing time will be shorter for this particular filter).

Even if you use a non streamed writer, each filter which has a ThreadedGenerateData() will split the image into two and send each part to one thread and you will notice two calls to the function.

If you have some particular requirement and want to use only one thread, you can call the SetNumberOfThreads() method on each of your filter.

When you are writing your own filter, you have to follow some rules to make your filter streamable and threadable. Some details are provided in sections 28.3 and 28.4.

27.3 Division strategies

The division of the image occurs generally at the writer level. Different strategies are available and can be specified explicitly. In OTB, these are referred as *splitter*. Several available splitters are:

- `itk::ImageRegionSplitter`
- `itk::ImageRegionMultidimensionalSplitter`
- `otb::ImageRegionNonUniformMultidimensionalSplitter`

You can add your own strategies based on these examples.

To change the splitting strategy of the writer, you can use the following model:

```
typedef otb::ImageRegionNonUniformMultidimensionalSplitter<3> splitterType;
splitterType::Pointer splitter=splitterType::New() ;
writer->SetRegionSplitter(splitter);
```

CHAPTER

TWENTYEIGHT

HOW TO WRITE A FILTER

This purpose of this chapter is help developers create their own filter (process object). This chapter is divided into four major parts. An initial definition of terms is followed by an overview of the filter creation process. Next, data streaming is discussed. The way data is streamed in ITK must be understood in order to write correct filters. Finally, a section on multithreading describes what you must do in order to take advantage of shared memory parallel processing.

28.1 Terminology

The following is some basic terminology for the discussion that follows. Chapter 3 provides additional background information.

- The **data processing pipeline** is a directed graph of **process** and **data objects**. The pipeline inputs, operators on, and outputs data.
- A **filter**, or **process object**, has one or more inputs, and one or more outputs.
- A **source**, or source process object, initiates the data processing pipeline, and has one or more outputs.
- A **mapper**, or mapper process object, terminates the data processing pipeline. The mapper has one or more outputs, and may write data to disk, interface with a display system, or interface to any other system.
- A **data object** represents and provides access to data. In ITK, the data object (ITK class `itk::DataObject`) is typically of type `otb::Image` or `itk::Mesh`.
- A **region** (ITK class `itk::Region`) represents a piece, or subset of the entire data set.
- An **image region** (ITK class `itk::ImageRegion`) represents a structured portion of data. ImageRegion is implemented using the `itk::Index` and `itk::Size` classes

- A **mesh region** (ITK class `itk::MeshRegion`) represents an unstructured portion of data.
- The **LargestPossibleRegion** is the theoretical single, largest piece (region) that could represent the entire dataset. The LargestPossibleRegion is used in the system as the measure of the largest possible data size.
- The **BufferedRegion** is a contiguous block of memory that is less than or equal to in size to the LargestPossibleRegion. The buffered region is what has actually been allocated by a filter to hold its output.
- The **RequestedRegion** is the piece of the dataset that a filter is required to produce. The RequestedRegion is less than or equal in size to the BufferedRegion. The RequestedRegion may differ in size from the BufferedRegion due to performance reasons. The RequestedRegion may be set by a user, or by an application that needs just a portion of the data.
- The **modified time** (represented by ITK class `itk::TimeStamp`) is a monotonically increasing integer value that characterizes a point in time when an object was last modified.
- **Downstream** is the direction of dataflow, from sources to mappers.
- **Upstream** is the opposite of downstream, from mappers to sources.
- The **pipeline modified time** for a particular data object is the maximum modified time of all upstream data objects and process objects.
- The term **information** refers to metadata that characterizes data. For example, index and dimensions are information characterizing an image region.

28.2 Overview of Filter Creation

Filters are defined with respect to the type of data they input (if any), and the type of data they output (if any). The key to writing a ITK filter is to identify the number and types of input and output. Having done so, there are often superclasses that simplify this task via class derivation. For example, most filters in ITK take a single image as input, and produce a single image on output. The superclass `itk::ImageToImageFilter` is a convenience class that provide most of the functionality needed for such a filter.

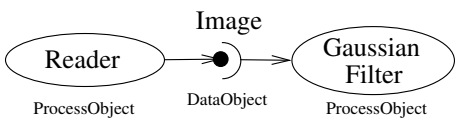


Figure 28.1: Relationship between DataObject and ProcessObject.

Some common base classes for new filters include:

- `ImageToImageFilter`: the most common filter base for segmentation algorithms. Takes an image and produces a new image, by default of the same dimensions. Override `GenerateOutputInformation` to produce a different size.
- `UnaryFunctorImageFilter`: used when defining a filter that applies a function to an image.
- `BinaryFunctorImageFilter`: used when defining a filter that applies an operation to two images.
- `ImageFunction`: a functor that can be applied to an image, evaluating $f(x)$ at each point in the image.
- `MeshToMeshFilter`: a filter that transforms meshes, such as tessellation, polygon reduction, and so on.
- `LightObject`: abstract base for filters that don't fit well anywhere else in the class hierarchy. Also useful for "calculator" filters; ie. a sink filter that takes an input and calculates a result which is retrieved using a `Get()` method.

Once the appropriate superclass is identified, the filter writer implements the class defining the methods required by most all ITK objects: `New()`, `PrintSelf()`, and protected constructor, copy constructor, delete, and operator=, and so on. Also, don't forget standard typedefs like `Self`, `Superclass`, `Pointer`, and `ConstPointer`. Then the filter writer can focus on the most important parts of the implementation: defining the API, data members, and other implementation details of the algorithm. In particular, the filter writer will have to implement either a `GenerateData()` (non-threaded) or `ThreadedGenerateData()` method. (See Section 3.2.7 for an overview of multithreading in ITK.)

An important note: the GenerateData() method is required to allocate memory for the output. The ThreadedGenerateData() method is not. In default implementation (see `itk::ImageSource`, a superclass of `itk::ImageToImageFilter`) `GenerateData()` allocates memory and then invokes `ThreadedGenerateData()`.

One of the most important decisions that the developer must make is whether the filter can stream data; that is, process just a portion of the input to produce a portion of the output. Often superclass behavior works well: if the filter processes the input using single pixel access, then the default behavior is adequate. If not, then the user may have to a) find a more specialized superclass to derive from, or b) override one or more methods that control how the filter operates during pipeline execution. The next section describes these methods.

28.3 Streaming Large Data

The data associated with multi-dimensional images is large and becoming larger. This trend is due to advances in scanning resolution, as well as increases in computing capability. Any practical seg-

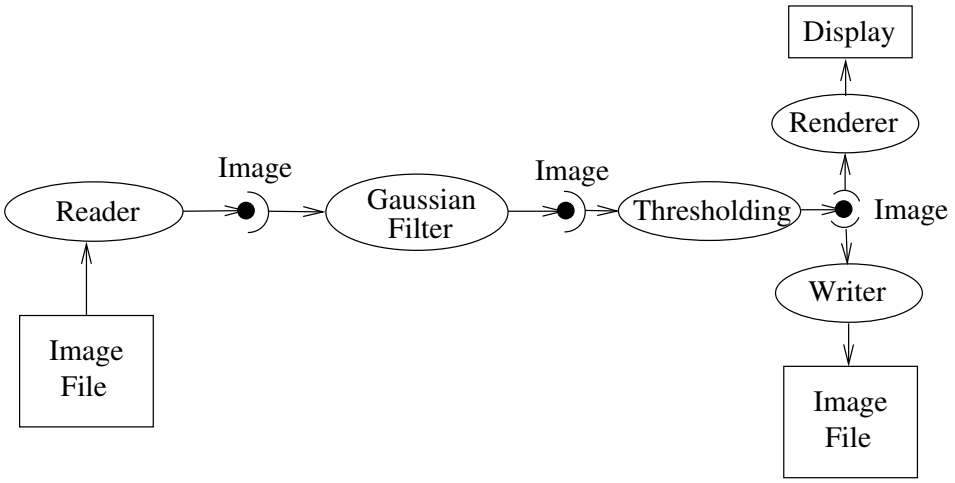


Figure 28.2: The Data Pipeline

mentation and registration software system must address this fact in order to be useful in application. ITK addresses this problem via its data streaming facility.

In ITK, streaming is the process of dividing data into pieces, or regions, and then processing this data through the data pipeline. Recall that the pipeline consists of process objects that generate data objects, connected into a pipeline topology. The input to a process object is a data object (unless the process initiates the pipeline and then it is a source process object). These data objects in turn are consumed by other process objects, and so on, until a directed graph of data flow is constructed. Eventually the pipeline is terminated by one or more mappers, that may write data to storage, or interface with a graphics or other system. This is illustrated in figures 28.1 and 28.2.

A significant benefit of this architecture is that the relatively complex process of managing pipeline execution is designed into the system. This means that keeping the pipeline up to date, executing only those portions of the pipeline that have changed, multithreading execution, managing memory allocation, and streaming is all built into the architecture. However, these features do introduce complexity into the system, the bulk of which is seen by class developers. The purpose of this chapter is to describe the pipeline execution process in detail, with a focus on data streaming.

28.3.1 Overview of Pipeline Execution

The pipeline execution process performs several important functions.

1. It determines which filters, in a pipeline of filters, need to execute. This prevents redundant execution and minimizes overall execution time.

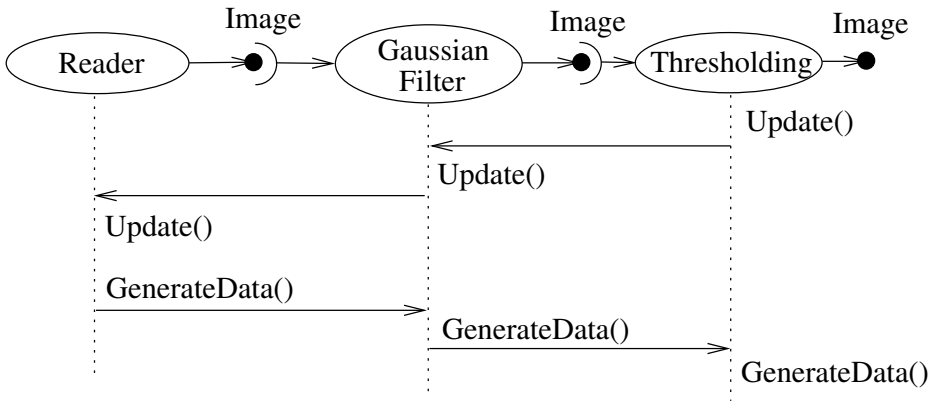


Figure 28.3: Sequence of the Data Pipeline updating mechanism

2. It initializes the (filter's) output data objects, preparing them for new data. In addition, it determines how much memory each filter must allocate for its output, and allocates it.

3. The execution process determines how much data a filter must process in order to produce an output of sufficient size for downstream filters; it also takes into account any limits on memory or special filter requirements. Other factors include the size of data processing kernels, that affect how much data input data (extra padding) is required.

4. It subdivides data into subpieces for multithreading. (Note that the division of data into subpieces is exactly same problem as dividing data into pieces for streaming; hence multithreading comes for free as part of the streaming architecture.)

5. It may free (or release) output data if filters no longer need it to compute, and the user requests that data is to be released. (Note: a filter's output data object may be considered a "cache". If the cache is allowed to remain (`ReleaseDataFlagOff()`) between pipeline execution, and the filter, or the input to the filter, never changes, then process objects downstream of the filter just reuse the filter's cache to re-execute.)

To perform these functions, the execution process negotiates with the filters that define the pipeline. Only each filter can know how much data is required on input to produce a particular output. For example, a shrink filter with a shrink factor of two requires an image twice as large (in terms of its x-y dimensions) on input to produce a particular size output. An image convolution filter would require extra input (boundary padding) depending on the size of the convolution kernel. Some filters require the entire input to produce an output (for example, a histogram), and have the option of requesting the entire input. (In this case streaming does not work unless the developer creates a filter that can request multiple pieces, caching state between each piece to assemble the final output.)

Ultimately the negotiation process is controlled by the request for data of a particular size (i.e., region). It may be that the user asks to process a region of interest within a large image, or that

memory limitations result in processing the data in several pieces. For example, an application may compute the memory required by a pipeline, and then use `itk::StreamingImageFilter` to break the data processing into several pieces. The data request is propagated through the pipeline in the upstream direction, and the negotiation process configures each filter to produce output data of a particular size.

The secret to creating a streaming filter is to understand how this negotiation process works, and how to override its default behavior by using the appropriate virtual functions defined in `itk::ProcessObject`. The next section describes the specifics of these methods, and when to override them. Examples are provided along the way to illustrate concepts.

28.3.2 Details of Pipeline Execution

Typically pipeline execution is initiated when a process object receives the `ProcessObject::Update()` method invocation. This method is simply delegated to the output of the filter, invoking the `DataObject::Update()` method. Note that this behavior is typical of the interaction between ProcessObject and DataObject: a method invoked on one is eventually delegated to the other. In this way the data request from the pipeline is propagated upstream, initiating data flow that returns downstream.

The `DataObject::Update()` method in turn invokes three other methods:

- `DataObject::UpdateOutputInformation()`
- `DataObject::PropagateRequestedRegion()`
- `DataObject::UpdateOutputData()`

UpdateOutputInformation()

The `UpdateOutputInformation()` method determines the pipeline modified time. It may set the RequestedRegion and the LargestPossibleRegion depending on how the filters are configured. (The RequestedRegion is set to process all the data, i.e., the LargestPossibleRegion, if it has not been set.) The UpdateOutputInformation() propagates upstream through the entire pipeline and terminates at the sources.

During `UpdateOutputInformation()`, filters have a chance to override the `ProcessObject::GenerateOutputInformation()` method (`GenerateOutputInformation()` is invoked by `UpdateOutputInformation()`). The default behavior is for the `GenerateOutputInformation()` to copy the metadata describing the input to the output (via `DataObject::CopyInformation()`). Remember, information is metadata describing the output, such as the origin, spacing, and LargestPossibleRegion (i.e., largest possible size) of an image.

A good example of this behavior is `itk::ShrinkImageFilter`. This filter takes an input image and shrinks it by some integral value. The result is that the spacing and LargestPossibleRegion of the output will be different to that of the input. Thus, `GenerateOutputInformation()` is overloaded.

PropagateRequestedRegion()

The `PropagateRequestedRegion()` call propagates upstream to satisfy a data request. In typical application this data request is usually the LargestPossibleRegion, but if streaming is necessary, or the user is interested in updating just a portion of the data, the RequestedRegion may be any valid region within the LargestPossibleRegion.

The function of `PropagateRequestedRegion()` is, given a request for data (the amount is specified by RequestedRegion), propagate upstream configuring the filter's input and output process object's to the correct size. Eventually, this means configuring the BufferedRegion, that is the amount of data actually allocated.

The reason for the buffered region is this: the output of a filter may be consumed by more than one downstream filter. If these consumers each request different amounts of input (say due to kernel requirements or other padding needs), then the upstream, generating filter produces the data to satisfy both consumers, that may mean it produces more data than one of the consumers needs.

The `ProcessObject::PropagateRequestedRegion()` method invokes three methods that the filter developer may choose to overload.

- `EnlargeOutputRequestedRegion(DataObject *output)` gives the (filter) subclass a chance to indicate that it will provide more data than required for the output. This can happen, for example, when a source can only produce the whole output (i.e., the LargestPossibleRegion).
- `GenerateOutputRequestedRegion(DataObject *output)` gives the subclass a chance to define how to set the requested regions for each of its outputs, given this output's requested region. The default implementation is to make all the output requested regions the same. A subclass may need to override this method if each output is a different resolution. This method is only overridden if a filter has multiple outputs.
- `GenerateInputRequestedRegion()` gives the subclass a chance to request a larger requested region on the inputs. This is necessary when, for example, a filter requires more data at the "internal" boundaries to produce the boundary values - due to kernel operations or other region boundary effects.

`itk::RGBGibbsPriorFilter` is an example of a filter that needs to invoke `EnlargeOutputRequestedRegion()`. The designer of this filter decided that the filter should operate on all the data. Note that a subtle interplay between this method and `GenerateInputRequestedRegion()` is occurring here. The default behavior of `GenerateInputRequestedRegion()` (at least for `itk::ImageToImageFilter`) is to set the

input RequestedRegion to the output's ReqestedRegion. Hence, by overriding the method `EnlargeOutputRequestedRegion()` to set the output to the LargestPossibleRegion, effectively sets the input to this filter to the LargestPossibleRegion (and probably causing all upstream filters to process their LargestPossibleRegion as well. This means that the filter, and therefore the pipeline, does not stream. This could be fixed by reimplementing the filter with the notion of streaming built in to the algorithm.)

`itk::GradientMagnitudeImageFilter` is an example of a filter that needs to invoke `GenerateInputRequestedRegion()`. It needs a larger input requested region because a kernel is required to compute the gradient at a pixel. Hence the input needs to be "padded out" so the filter has enough data to compute the gradient at each output pixel.

UpdateOutputData()

`UpdateOutputData()` is the third and final method as a result of the `Update()` method. The purpose of this method is to determine whether a particular filter needs to execute in order to bring its output up to date. (A filter executes when its `GenerateData()` method is invoked.) Filter execution occurs when a) the filter is modified as a result of modifying an instance variable; b) the input to the filter changes; c) the input data has been released; or d) an invalid RequestedRegion was set previously and the filter did not produce data. Filters execute in order in the downstream direction. Once a filter executes, all filters downstream of it must also execute.

`DataObject::UpdateOutputData()` is delegated to the DataObject's source (i.e., the ProcessObject that generated it) only if the DataObject needs to be updated. A comparison of modified time, pipeline time, release data flag, and valid requested region is made. If any one of these conditions indicate that the data needs regeneration, then the source's `ProcessObject::UpdateOutputData()` is invoked. These calls are made recursively up the pipeline until a source filter object is encountered, or the pipeline is determined to be up to date and valid. At this point, the recursion unrolls, and the execution of the filter proceeds. (This means that the output data is initialized, StartEvent is invoked, the filters `GenerateData()` is called, EndEvent is invoked, and input data to this filter may be released, if requested. In addition, this filter's InformationTime is updated to the current time.)

The developer will never override `UpdateOutputData()`. The developer need only write the `GenerateData()` method (non-threaded) or `ThreadedGenerateData()` method. A discussion of threading follows in the next section.

28.4 Threaded Filter Execution

Filters that can process data in pieces can typically multi-process using the data parallel, shared memory implementation built into the pipeline execution process. To create a multithreaded filter, simply define and implement a `ThreadedGenerateData()` method. For example, a `itk::ImageToImageFilter` would create the method:

```
void ThreadedGenerateData(const OutputImageRegionType&
                          outputRegionForThread, int threadId)
```

The key to threading is to generate output for the output region given (as the first parameter in the argument list above). In ITK, this is simple to do because an output iterator can be created using the region provided. Hence the output can be iterated over, accessing the corresponding input pixels as necessary to compute the value of the output pixel.

Multi-threading requires caution when performing I/O (including using `cout` or `cerr`) or invoking events. A safe practice is to allow only thread id zero to perform I/O or generate events. (The thread id is passed as argument into `ThreadedGenerateData()`). If more than one thread tries to write to the same place at the same time, the program can behave badly, and possibly even deadlock or crash.

28.5 Filter Conventions

In order to fully participate in the ITK pipeline, filters are expected to follow certain conventions, and provide certain interfaces. This section describes the minimum requirements for a filter to integrate into the ITK framework.

The class declaration for a filter should include the macro `ITK_EXPORT`, so that on certain platforms an export declaration can be included.

A filter should define public types for the class itself (`Self`) and its `Superclass`, and `const` and non-`const` smart pointers, thus:

```
typedef ExampleImageFilter                Self;
typedef ImageToImageFilter<TImage,TImage> Superclass;
typedef SmartPointer<Self>                Pointer;
typedef SmartPointer<const Self>          ConstPointer;
```

The `Pointer` type is particularly useful, as it is a smart pointer that will be used by all client code to hold a reference-counted instantiation of the filter.

Once the above types have been defined, you can use the following convenience macros, which permit your filter to participate in the object factory mechanism, and to be created using the canonical `::New()`:

```
/** Method for creation through the object factory. */
itkNewMacro(Self);

/** Run-time type information (and related methods). */
itkTypeMacro(ExampleImageFilter, ImageToImageFilter);
```

The default constructor should be `protected`, and provide sensible defaults (usually zero) for all parameters. The copy constructor and assignment operator should be declared `private` and not implemented, to prevent instantiating the filter without the factory methods (above).

Finally, the template implementation code (in the `.txx` file) should be included, bracketed by a test for manual instantiation, thus:

```
#ifndef ITK_MANUAL_INSTANTIATION
#include "itkExampleFilter.txx"
#endif
```

28.5.1 Optional

A filter can be printed to an `std::ostream` (such as `std::cout`) by implementing the following method:

```
void PrintSelf( std::ostream& os, Indent indent ) const;
```

and writing the name-value pairs of the filter parameters to the supplied output stream. This is particularly useful for debugging.

28.5.2 Useful Macros

Many convenience macros are provided by ITK, to simplify filter coding. Some of these are described below:

itkStaticConstMacro Declares a static variable of the given type, with the specified initial value.

itkGetMacro Defines an accessor method for the specified scalar data member. The convention is for data members to have a prefix of `m_`.

itkSetMacro Defines a mutator method for the specified scalar data member, of the supplied type. This will automatically set the `Modified` flag, so the filter stage will be executed on the next `Update()`.

itkBooleanMacro Defines a pair of `OnFlag` and `OffFlag` methods for a boolean variable `m_Flag`.

itkGetObjectMacro, itkSetObjectMacro Defines an accessor and mutator for an ITK object. The Get form returns a smart pointer to the object.

Much more useful information can be learned from browsing the source in `Code/Common/itkMacro.h` and for the `itk::Object` and `itk::LightObject` classes.

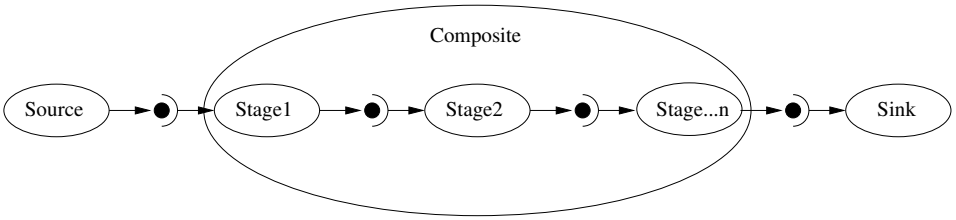


Figure 28.4: A Composite filter encapsulates a number of other filters.

28.6 How To Write A Composite Filter

In general, most ITK/OTB filters implement one particular algorithm, whether it be image filtering, an information metric, or a segmentation algorithm. In the previous section, we saw how to write new filters from scratch. However, it is often very useful to be able to make a new filter by combining two or more existing filters, which can then be used as a building block in a complex pipeline. This approach follows the Composite pattern [48], whereby the composite filter itself behaves just as a regular filter, providing its own (potentially higher level) interface and using other filters (whose detail is hidden to users of the class) for the implementation. This composite structure is shown in Figure 28.4, where the various `Stage-n` filters are combined into one by the `Composite` filter. The `Source` and `Sink` filters only see the interface published by the `Composite`. Using the Composite pattern, a composite filter can encapsulate a pipeline of arbitrary complexity. These can in turn be nested inside other pipelines.

28.6.1 Implementing a Composite Filter

There are a few considerations to take into account when implementing a composite filter. All the usual requirements for filters apply (as discussed above), but the following guidelines should be considered:

1. The template arguments it takes must be sufficient to instantiate all of the component filters. Each component filter needs a type supplied by either the implementor or the enclosing class. For example, an `ImageToImageFilter` normally takes an input and output image type (which may be the same). But if the output of the composite filter is a classified image, we need to either decide on the output type inside the composite filter, or restrict the choices of the user when she/he instantiates the filter.

2. The types of the component filters should be declared in the header, preferably with `protected` visibility. This is because the internal structure normally should not be visible to users of the class, but should be to descendent classes that may need to modify or customize the behavior.

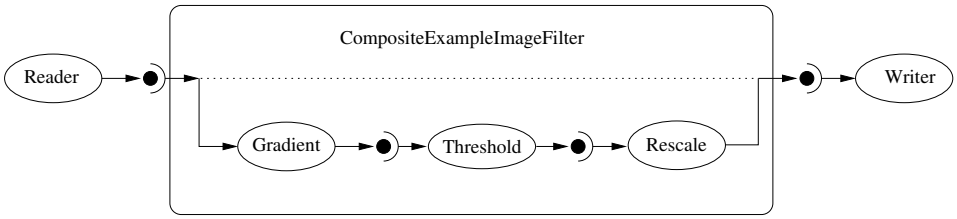


Figure 28.5: Example of a typical composite filter. Note that the output of the last filter in the internal pipeline must be grafted into the output of the composite filter.

3. The component filters should be private data members of the composite class, as in `FilterType::Pointer`.
4. The default constructor should build the pipeline by creating the stages and connect them together, along with any default parameter settings, as appropriate.
5. The input and output of the composite filter need to be grafted on to the head and tail (respectively) of the component filters.

This grafting process is illustrated in Figure 28.5.

28.6.2 A Simple Example

The source code for this example can be found in the file `Examples/Filtering/CompositeFilterExample.cxx`.

The composite filter we will build combines three filters: a gradient magnitude operator, which will calculate the first-order derivative of the image; a thresholding step to select edges over a given strength; and finally a rescaling filter, to ensure the resulting image data is visible by scaling the intensity to the full spectrum of the output image type.

Since this filter takes an image and produces another image (of identical type), we will specialize the ImageToImageFilter:

```
#include "itkImageToImageFilter.h"
```

Next we include headers for the component filters:

```
#include "itkGradientMagnitudeImageFilter.h"
#include "itkThresholdImageFilter.h"
#include "itkRescaleIntensityImageFilter.h"
```

Now we can declare the filter itself. It is within the OTB namespace, and we decide to make it use the same image type for both input and output, thus the template declaration needs only one

parameter. Deriving from `ImageToImageFilter` provides default behavior for several important aspects, notably allocating the output image (and making it the same dimensions as the input).

```
namespace otb
{

template <class TImageType>
class ITK_EXPORT CompositeExampleImageFilter :
  public itk::ImageToImageFilter<TImageType, TImageType>
{
public:
```

Next we have the standard declarations, used for object creation with the object factory:

```
  typedef CompositeExampleImageFilter                      Self;
  typedef itk::ImageToImageFilter<TImageType, TImageType> Superclass;
  typedef itk::SmartPointer<Self>                          Pointer;
  typedef itk::SmartPointer<const Self>                    ConstPointer;
```

Here we declare an alias (to save typing) for the image's pixel type, which determines the type of the threshold value. We then use the convenience macros to define the Get and Set methods for this parameter.

```
  typedef typename TImageType::PixelType PixelType;

  itkGetMacro(Threshold, PixelType);
  itkSetMacro(Threshold, PixelType);
```

Now we can declare the component filter types, templated over the enclosing image type:

```
protected:

  typedef itk::ThresholdImageFilter<TImageType> ThresholdType;
  typedef itk::GradientMagnitudeImageFilter<TImageType, TImageType>
  GradientType;
  typedef itk::RescaleIntensityImageFilter<TImageType, TImageType>
  RescalerType;
```

The component filters are declared as data members, all using the smart pointer types.

```
  typename GradientType::Pointer m_GradientFilter;
  typename ThresholdType::Pointer m_ThresholdFilter;
  typename RescalerType::Pointer m_RescaleFilter;

  PixelType m_Threshold;
};

} /* namespace otb */
```

The constructor sets up the pipeline, which involves creating the stages, connecting them together, and setting default parameters.

```
template <class TImageType>
CompositeExampleImageFilter<TImageType>
::CompositeExampleImageFilter()
{
  m_GradientFilter = GradientType::New();
  m_ThresholdFilter = ThresholdType::New();
  m_RescaleFilter = RescalerType::New();

  m_ThresholdFilter->SetInput(m_GradientFilter->GetOutput());
  m_RescaleFilter->SetInput(m_ThresholdFilter->GetOutput());

  m_Threshold = 1;

  m_RescaleFilter->SetOutputMinimum(
    itk::NumericTraits<PixelType>::NonpositiveMin());
  m_RescaleFilter->SetOutputMaximum(itk::NumericTraits<PixelType>::max());
}
```

The `GenerateData()` is where the composite magic happens. First, we connect the first component filter to the inputs of the composite filter (the actual input, supplied by the upstream stage). Then we graft the output of the last stage onto the output of the composite, which ensures the filter regions are updated. We force the composite pipeline to be processed by calling `Update()` on the final stage, then graft the output back onto the output of the enclosing filter, so it has the result available to the downstream filter.

```
template <class TImageType>
void
CompositeExampleImageFilter<TImageType>::
GenerateData()
{
  m_GradientFilter->SetInput(this->GetInput());

  m_ThresholdFilter->ThresholdBelow(this->m_Threshold);

  m_RescaleFilter->GraftOutput(this->GetOutput());
  m_RescaleFilter->Update();
  this->GraftOutput(m_RescaleFilter->GetOutput());
}
```

Finally we define the `PrintSelf` method, which (by convention) prints the filter parameters. Note how it invokes the superclass to print itself first, and also how the indentation prefixes each line.

```
template <class TImageType>
void
CompositeExampleImageFilter<TImageType>::
PrintSelf(std::ostream& os, itk::Indent indent) const
{
  Superclass::PrintSelf(os, indent);

  os
  << indent << "Threshold:" << this->m_Threshold
  << std::endl;
```

```
}

} /* end namespace otb */
```

It is important to note that in the above example, none of the internal details of the pipeline were exposed to users of the class. The interface consisted of the Threshold parameter (which happened to change the value in the component filter) and the regular ImageToImageFilter interface. This example pipeline is illustrated in Figure 28.5.

CHAPTER

TWENTYNINE

PERSISTENT FILTERS

29.1 Introduction

As presented in chapter 27, OTB has two main mechanisms to handle efficiently large data: streaming allows to process image piece-wise, and multi-threading allows to process concurrently several pieces of one streaming block. Using these concepts, one can easily write pixel-wise or neighborhood-based filters and insert them into a pipeline which will be scalable with respect to the input image size.

Yet, sometimes we need to compute global features on the whole image. One example is to determine image mean and variance of the input image in order to produce a centered and reduced image. The operation of centering and reducing each pixel is fully compliant with streaming and threading, but one has to first estimate the mean and variance of the image. This first step requires to walk the whole image once, and traditional streaming and multi-threading based filter architecture is of no help here.

This is because there is a fundamental difference between these two operations: one supports streaming, and the other needs to perform streaming. In fact we would like to stream the whole image piece by piece through some filter that will collect and keep mean and variance cumulants, and then synthetize theses cumulants to compute the final mean and variance once the full image as been streamed. Each stream would also benefit from parallel processing. This is exactly what persistent filters are for.

29.2 Architecture

There are two main objects in the persistent filters framework. The first is the `otb::PersistentImageFilter`, the second is the `otb::PersistentFilterStreamingDecorator`.

29.2.1 The persistent filter class

The `otb::PersistentImageFilter` class is a regular `itk::ImageToImageFilter`, with two additional pure virtual methods: the `Synthetize()` and the `Reset()` methods.

Imagine that the `GenerateData()` or `ThreadedGenerateData()` progressively computes some global feature of the whole image, using some member of the class to store intermediate results. The `Synthetize()` is an additional method which is designed to be called one the whole image has been processed, in order to compute the final results from the intermediate results. The `Reset()` method is designed to allow the reset of the intermediate results members so as to start a fresh processing.

Any sub-class of the `otb::PersistentImageFilter` can be used as a regular `itk::ImageToImageFilter` (provided that both `Synthetize()` and `Reset()` have been implemented, but the real interest of these filters is to be used with the streaming decorator class presented in the next section.

29.2.2 The streaming decorator class

The `otb::PersistentFilterStreamingDecorator` is a class designed to be templated with subclasses of the `otb::PersistentImageFilter`. It provides the mechanism to stream the whole image through the templated filter, using a third class called `otb::StreamingImageVirtualWriter`. When the `Update()` method is called on a `otb::PersistentImageFilterStreamingDecorator`, a pipeline plugging the templated subclass of the `otb::PersistentImageFilter` to an instance of `otb::StreamingImageVirtualWriter` is created. The latter is then updated, and acts like a regular `otb::ImageFileWriter` but it does not actually write anything to the disk : streaming pieces are requested and immediately discarded. The `otb::PersistentImageFilterStreamingDecorator` also calls the `Reset()` method at the beginning and the `Synthetize()` method at the end of the streaming process. Therefore, it packages the whole mechanism for the use of a `otb::PersistentImageFilter`:

1. Call the `Reset()` method on the filter so as to reset any temporary results members,
2. Stream the image piece-wise through the filter,
3. Call the `Synthetize()` method on the filter so as to compute the final results.

There are some methods that allows to tune the behavior of the `otb::StreamingImageVirtualWriter`, allowing to change the image splitting methods (tiles or strips) or the size of the streams with respect to some target available amount of memory. Please see the class documentation for details. The instance of the `otb::StreamingImageVirtualWriter` can be retrieved from the `otb::PersistentImageFilterStreamingDecorator` through the `GetStreamer()` method.

Though the internal filter of the `otb::PersistentImageFilterStreamingDecorator` can be accessed through the `GetFilter()` method, the class is often derived to package the streaming-decorated filter and wrap the parameters setters and getters.

29.3 An end-to-end example

This is an end-to-end example to compute the mean over a full image, using a streaming and threading-enabled filter. Please note that only specific details are explained here. For more general information on how to write a filter, please refer to section 28, page 605.

29.3.1 First step: writing a persistent filter

The first step is to write a persistent mean image filter. We need to include the appropriate header :

```
#include "otbPersistentImageFilter.h"
```

Then, we declare the class prototype as follows:

```
template<class TInputImage >
  class ITK_EXPORT PersistentMeanImageFilter :
    public PersistentImageFilter<TInputImage, TInputImage>
```

Since the output image will only be used for streaming purpose, we do not need to declare different input and output template types.

In the *private* section of the class, we will declare a member which will be used to store temporary results, and a member which will be used to store the final result.

```
private:
  // Temporary results container
  std::vector<PixelType> m_TemporarySums;

  // Final result member
  double m_Mean;
```

Next, we will write the `Reset()` method implementation in the *protected* section of the class. Proper allocation of the temporary results container with respect to the number of threads is handled here.

```
protected:
  virtual void Reset()
  {
  // Retrieve the number of threads
  unsigned int numberOfThreads = this->GetNumberOfThreads();

  // Reset the temporary results container
  m_TemporarySums = std::vector<PixelType>(numberOfThreads,
                                           itk::NumericTraits<PixelType>::Zero);
```

```
  // Reset the final result
  m_Mean = 0.;
  }
```

Now, we need to write the `ThreadedGenerateData()` methods (also in the *protected* section), were temporary results will be computed for each piece of stream.

```
virtual void ThreadedGenerateData(const RegionType&
                                  outputRegionForThread, int threadId)
{
// Enable progress reporting
itk::ProgressReporter(this,threadId,outputRegionForThread.GetNumberOfPixels());

// Retrieve the input pointer
InputImagePointer inputPtr = const_cast<TInputImage *>(this->GetInput());

// Declare an iterator on the region
itk::ImageRegionConstIteratorWithIndex<TInputImage> it(inputPtr,
outputRegionForThread);

// Walk the region of the image with the iterator
for (it.GoToBegin(); !it.IsAtEnd(); ++it, progress.CompletedPixel())
  {
  // Retrieve pixel value
  const PixelType& value = it.Get();

  // Update temporary results for the current thread
  m_TemporarySums[threadId]+= value;
}
```

Last, we need to define the `Synthetize()` method (still in the *protected* section), which will yield the final results:

```
virtual void Synthetize()
{
// For each thread
for(unsigned int threadId = 0; threadId <this->GetNumberOfThreads();++threadId)
  {
  // Update final result
  m_Mean+=m_TemporarySums[threadId];
}

// Complete calculus by dividing by the total number of pixels:
unsigned int nbPixels =
this->GetInput()->GetLargestPossibleRegion().GetNumberOfPixels();

if(nbPixels!=0)
  {
  m_Mean/=nbPixels;
  }
}
```

29.3.2 Second step: Decorating the filter and using it

Now, to use the filter, one only has to decorate it with the `otb::PersistentImageFilterStreamingDecorator`. First step is to include the appropriate header:

```
#include "otbPersistentMeanImageFilter.h"
#include "otbPersistentFilterStreamingDecorator.h"
```

Then, we decorate the filter with some typedefs:

```
typedef otb::PersistentMeanImageFilter<ImageType>
  PersitentMeanFilterType;
typedef otb::PersistentImageFilterStreamingDecorator
  < PersitentMeanFilterType > StreamingMeanFilterType;
```

Now, the decorated filter can be used like any standard filter:

```
StreamingMeanFilterType::Pointer filter =
  StreamingMeanFilterType::New();

filter->SetInput(reader->GetOutput());
filter->Update();
```

29.3.3 Third step: one class to rule them all

It is often convenient to avoid the few typedefs of the previous section by deriving a new class from the decorated filter:

```
template<class TInputImage >
  class ITK_EXPORT StreamingMeanImageFilter :
    public PersistentImageFilterStreamingDecorator<
           PersistentImageFilter<TInputImage, TInputImage> >
```

This also allows to redefine setters and getters for parameters, avoiding to call the `GetFilter()` method to set them.

CHAPTER

THIRTY

HOW TO WRITE AN APPLICATION

This chapter presents the different steps to write your own application. It also contains a description of the framework surrounding the applications.

30.1 Application design

The first logical step is to define the role of your application:

- What is the function of your application ? Try to draw a box diagram to describe the design of your application. Note that you don't have to worry about opening and saving image (or vector data) files, this is handled by the framework.
- What variables (or data objects) must be exposed outside the application ? Try to make a list of the inputs, outputs and parameters of your application.

Then you should have a good vision of your application pipeline. Depending on the different filters used, the application can be streamed and threaded. The threading capabilities can be different between the filters so there is no overall threading parameter (by default, each filter has its own threading settings).

It is a different story for streaming. Since the image writers are handled within the framework and outside the reach of the developer, the default behaviour is to use streaming. If one of the filters doesn't support streaming, it will enlarge the requested output region to the largest possible region and the entire image will be processed at once. As a result, the developer doesn't have to handle streaming nor threading. However, there is a way to choose the number of streaming divisions (see section 30.2.4).

30.2 Architecture of the class

Every application derive from the class `otb::Wrapper::Application`. An application can't be templated. It must contain the standard class typedefs and a call to the `OTB_APPLICATION_EXPORT` macro.

There are also three methods to implement in a new application:

- `DoInit()`
- `DoUpdateParameters()`
- `DoExecute()`

30.2.1 DoInit()

This method is called once, when the application is instanciated. It should contain the following actions:

- Set the name and the description of the application
- Fill the documentation and give an example
- Declare all the parameters

30.2.2 DoUpdateParameters()

This method is called after every modification of a parameter value. With the command line launcher, it is called each time a parameter is loaded. With the Qt launcher, it is called each time a parameter field is modified. It can be used to maintain consistency et relationship between parameters (e.g. in ExtractROI: when changing the input image, maybe the ROI size has to be updated).

30.2.3 DoExecute()

This method contains the real action of the application. This is where the pipeline must be set up. The application framework provides different methods to get a value or an object associated to a parameter:

- `GetParameterInt(key)` : get the integer value of a parameter
- `GetParameterFloat(key)` : get the float value of a parameter
- `GetParameterString(key)` : get the string value of a parameter

- `GetParameterImage(key)` : get a pointer to an image object, read from the file name given in input
- ...

where `key` refers to parameter key, defined using `AddParameter()` method in `DoInit()` method.

Similar methods exist for binding a data object to an output parameter:

- `SetParameterOutputImage(key,data)` : link the image object to the given output parameter
- `SetParameterComplexOutputImage(key,data)` : link the complex image object to the given output parameter
- `SetParameterOutputVectorData(key,data)` : link the vector data object to the given output parameter

If possible, no filter update should be called inside this function. The update will be automatically called afterwards : for every image or vector data output, a writer is created and updated.

30.2.4 Parameters selection

In the new application framework, every input, output or parameter derive from `otb::Wrapper::Parameter`. The application engine supplies the following types of parameters:

- `ParameterType_Empty` : parameter without value (can be used to represent a flag)
- `ParameterType_Int` : parameter storing an integer.
- `ParameterType_Radius` : parameter storing a radius.
- `ParameterType_Float` : parameter storing a float.
- `ParameterType_String` : parameter storing character string.
- `ParameterType_StringList` : parameter storing a list of character string.
- `ParameterType_InputFilename` : parameter storing an input file name.
- `ParameterType_InputFilenameList` : parameter storing a list of input file names.
- `ParameterType_Directory` : parameter storing a folder name.
- `ParameterType_Group` : parameter storing children parameters.

- ParameterType_Choice : parameter storing a list of choices (doesn't support multi-choice). It also allows to create specific sub-parameters for each available choice.
- ParameterType_ListView : parameter storing a list of choices (support multi-choice).
- ParameterType_InputImage : parameter storing an input image.
- ParameterType_InputImageList : parameter storing a list of input image.
- ParameterType_ComplexInputImage : parameter storing a complex input image.
- ParameterType_InputVectorData : parameter storing input vector data.
- ParameterType_InputVectorDataList : parameter storing a list of input vector data.
- ParameterType_InputProcessXML : parameter storing an input XML file name.
- ParameterType_OutputFilename : parameter storing an output file name.
- ParameterType_OutputImage : parameter storing an output image.
- ParameterType_ComplexOutputImage : parameter storing a complex output image.
- ParameterType_OutputVectorData : parameter storing an output vector data.
- ParameterType_OutputProcessXML : parameter storing an output XML file name.
- ParameterType_RAM : parameter storing the maximum amount of RAM to be used.

30.2.5 Parameters description

Each created parameter has a unique key and several boolean flags to represent its state. These flags can be used to set a parameter optional or test if the user has modified the parameter value. The parameters are created in the DoInit() method, then the framework will set their value (either by parsing the command line or reading the graphical user interface). The DoExecute() method is called when all mandatory parameters have been given a value, which can be obtained with "Get" methods defined in otb::Wrapper::Application. Parameters are set mandatory (or not) using MandatoryOn(key) method (MandatoryOff(key)).

Some functions are specific to numeric parameters, such as SetMinimumParameterIntValue(key,value) or SetMaximumParameterFloatValue(key,value). By default, numeric parameters are treated as inputs. If your application outputs a number, you can use a numeric parameter and change its role by calling SetParameterRole(key,Role_Output).

The input types InputImage, InputImageList, ComplexInputImage, InputVectorData and InputVectorDataList store the name of the files to load, but they also encapsulate the readers needed to produce the input data.

The output types OutputImage, ComplexOutputImage and OutputVectorData store the name of the files to write, but they also encapsulate the corresponding writers.

30.3 Compile your application

In order to compile your application you must call the macro OTB_CREATE_APPLICATION in the *CMakelists.txt* file. This macro generates the lib *otbapp_XXX.so*, in (OTB_BINARY_DIR), where *XXX* refers to the class name. Don't forget to enable application building (see. 2.2.3 section).

30.4 Execute your application

their are different ways to launch applicatons :

CommandLine : The command line option is invoked using *otbApplicationLauncherCommandLine* executable followed by the classname, the application dir and the application parameters.

QT : Application can be encapsuled in Qt framework using *otbApplicationLauncherQt* executable followed by the classname and the application dir.

Python : A Python wrapper is also available.

30.5 Testing your application

It is possible to write application tests. They are quite similar to filters tests. The macro OTB_TEST_APPLICATION makes it easy to define a new test.

30.6 Application Example

The source code for this example can be found in the file Examples/Application/ApplicationExample.cxx.

This example illustrates the creation of an application. A new application is a class, which derives from otb::Wrapper::Application class. We start by including the needed header files.

```
#include "otbWrapperApplication.h"
#include "otbWrapperApplicationFactory.h"
```

Application class is defined in Wrapper namespace.

```
namespace Wrapper
{
```

ExampleApplication class is derived from Application class.

```
class ExampleApplication : public Application
```

Class declaration is followed by ITK public types for the class, the superclass and smart pointers.

```
  typedef ExampleApplication Self;
  typedef Application Superclass;
  typedef itk::SmartPointer<Self> Pointer;
  typedef itk::SmartPointer<const Self> ConstPointer;
```

Following macros are necessary to respect ITK object factory mechanisms. Please report to 28.5 for additional information.

```
  itkNewMacro(Self)
;

  itkTypeMacro(ExampleApplication, otb::Application)
;
```

otb::Application relies on three main private methods: DoInit(), DoUpdate(), and DoExecute(). Section 30.2 gives a description a these methods. DoInit() method contains class information and description, parameter set up, and example values. Application name and description are set using following methods :

SetName() Name of the application.

SetDescription() Set the short description of the class.

SetDocName() Set long name of the application (that can be displayed . . .).

SetDocLongDescription() This methods is used to describe the class.

SetDocLimitations() Set known limitations (threading, invalid pixel type . . .) or bugs.

SetDocAuthors() Set the application Authors. Author List. Format : ”John Doe, Winnie the Pooh” . . .

SetDocSeeAlso() If the application is related to one another, it can be mentioned.

```
    SetName("Example");
    SetDescription("This application opens an image and save it. "
      "Pay attention, it includes Latex snippets in order to generate "
      "software guide documentation");

    SetDocName("Example");
    SetDocLongDescription("The purpose of this application is "
      "to present parameters types,"
      " and Application class framework. "
      "It is used to generate Software guide documentation"
      " for Application chapter example.");
    SetDocLimitations("None");
```

```
    SetDocAuthors("OTB-Team");
    SetDocSeeAlso(" ");
```

AddDocTag() method categorize the application using relevant tags. Code/ApplicationEngine/otbWrapperTags.h contains some predefined tags defined in Tags namespace.

```
    AddDocTag(Tags::Analysis);
    AddDocTag("Test");
```

Application parameters declaration is done using AddParameter() method. AddParameter() requires Parameter type, its name and description. otb::Wrapper::Application class contains methods to set parameters characteristics.

```
    AddParameter(ParameterType_InputImage, "in", "Input Image");
    AddParameter(ParameterType_OutputImage, "out", "Output Image");
    AddParameter(ParameterType_Empty, "boolean", "Boolean");
    MandatoryOff("boolean");
    AddParameter(ParameterType_Int, "int", "Integer");
    MandatoryOff("int");
    SetDefaultParameterInt("int", 1);
    SetMinimumParameterIntValue("int", 0);
    SetMaximumParameterIntValue("int", 10);
    AddParameter(ParameterType_Float, "float", "Float");
    MandatoryOff("float");
    SetDefaultParameterFloat("float", 0.2);
    SetMinimumParameterFloatValue("float", -1.0);
    SetMaximumParameterFloatValue("float", 15.0);
    AddParameter(ParameterType_String, "string", "String");
    MandatoryOff("string");
    AddParameter(ParameterType_InputFilename, "filename", "File name");
    MandatoryOff("filename");
    AddParameter(ParameterType_Directory, "directory", "Directory name");
    MandatoryOff("directory");

    AddParameter(ParameterType_Choice, "choice", "Choice");
    AddChoice("choice.choice1", "Choice 1");
    AddChoice("choice.choice2", "Choice 2");
    AddChoice("choice.choice3", "Choice 3");
    AddParameter(ParameterType_Float, "choice.choice1.floatchoice1"
                 , "Float of choice1");
    SetDefaultParameterFloat("choice.choice1.floatchoice1", 0.125);
    AddParameter(ParameterType_Float, "choice.choice3.floatchoice3"
                 , "Float of choice3");
    SetDefaultParameterFloat("choice.choice3.floatchoice3", 5.0);

    AddParameter(ParameterType_Group, "ingroup", "Input Group");
    MandatoryOff("ingroup");
    AddParameter(ParameterType_Int, "ingroup.integer", "Integer of Group");
    MandatoryOff("ingroup.integer");
    AddParameter(ParameterType_Group, "ingroup.images", "Input Images Group");
    AddParameter(ParameterType_InputImage, "ingroup.images.inputimage"
                 , "Input Image");
    MandatoryOff("ingroup.images.inputimage");
```

```
  AddParameter(ParameterType_Group, "outgroup", "Output Group");
  MandatoryOff("outgroup");
  AddParameter(ParameterType_OutputImage, "outgroup.outputimage"
               , "Output Image");
  MandatoryOff("outgroup.outputimage");
  AddParameter(ParameterType_InputImageList, "il", "Input image list");
  MandatoryOff("il");

  AddParameter(ParameterType_ListView, "cl", "Output Image channels");
  AddChoice("cl.choice1", "cl.choice1");
  AddChoice("cl.choice2", "cl.choice2");
  MandatoryOff("cl");

  AddParameter(ParameterType_RAM, "ram", "Available RAM");
  SetDefaultParameterInt("ram", 256);
  MandatoryOff("ram");

  AddParameter(ParameterType_ComplexInputImage, "cin", "Input Complex Image");
  AddParameter(ParameterType_ComplexOutputImage, "cout", "Output Complex Image");
  MandatoryOff("cin");
  MandatoryOff("cout");
```

An example commandline is automatically generated. Method `SetDocExampleParameterValue()` is used to set parameters. Dataset should be located in `OTB-Data/Examples` directory.

```
  SetDocExampleParameterValue("boolean", "true");
  SetDocExampleParameterValue("in", "QB_Suburb.png");
  SetDocExampleParameterValue("out", "Application_Example.png");
```

`DoUpdateParameters()` is called as soon as a parameter value change. Section 30.2.2 gives a complete description of this method.

```
void DoUpdateParameters()
{
}
```

`DoExecute()` contains the application core. Section 30.2.3 gives a complete description of this method.

```
void DoExecute()
{
  FloatVectorImageType::Pointer inImage = GetParameterImage("in");

  int paramInt = GetParameterInt("int");
  otbAppLogDEBUG( << paramInt <<std::endl );
  int paramFloat = GetParameterFloat("float");
  otbAppLogINFO( << paramFloat );

  SetParameterOutputImage("out", inImage);
}
```

Finally `OTB_APPLICATION_EXPORT` is called.

```
OTB_APPLICATION_EXPORT(otb::Wrapper::ExampleApplication)
```

Part V

Appendix

CHAPTER

THIRTYONE

FREQUENTLY ASKED QUESTIONS

31.1 Introduction

31.1.1 What is OTB?

OTB, the ORFEO Toolbox is a library of image processing algorithms developed by CNES in the frame of the ORFEO Accompaniment Program. OTB is based on the medical image processing library ITK, `http://www.itk.org`, and offers particular functionalities for remote sensing image processing in general and for high spatial resolution images in particular.

OTB provides:

- image access: optimized read/write access for most of remote sensing image formats, metadata access, simple visualization;
- sensor geometry: sensor models, cartographic projections;
- radiometry: atmospheric corrections, vegetation indices;
- filtering: blurring, denoising, enhancement;
- fusion: image pansharpening;
- feature extraction: interest points, alignments, lines;
- image segmentation: region growing, watershed, level sets;
- classification: K-means, SVM, Markov random fields;
- change detection.
- object based image analysis.
- geospatial analysis.

Many of these functionalities are provided by ITK and have been tested and documented for the use with remote sensing data.

You can get more information on OTB on the web at `http://www.orfeo-toolbox.org`.

31.1.2 What is ORFEO?

ORFEO stands for Optical and Radar Federated Earth Observation. In 2001 a cooperation program was set between France and Italy to develop ORFEO, an Earth observation dual system with metric resolution: Italy is in charge of COSMO-Skymed the radar component development, and France of PLEIADES the optic component.

The PLEIADES optic component is composed of two ”small satellites” (mass of one ton) offering a spatial resolution at nadir of 0.7 m and a field of view of 20 km. Their great agility enables a daily access all over the world, essentially for defense and civil security applications, and a coverage capacity necessary for the cartography kind of applications at scales better than those accessible to SPOT family satellites. Moreover, PLEIADES have stereoscopic acquisition capacity to meet the fine cartography needs, notably in urban regions, and to bring more information when used with aerial photography.

The ORFEO ”targeted” acquisition capacities made it a system particularly adapted to defense or civil security missions, as well as critical geophysical phenomena survey such as volcanic eruptions, which require a priority use of the system resources.

With respect to the constraints of the Franco-Italian agreement, cooperation have been set up for the PLEIADES optical component with Sweden, Belgium, Spain and Austria.

Where can I get more information about ORFEO?

At the PLEIADES HR web site: `http://smsc.cnes.fr/PLEIADES/`.

31.1.3 What is the ORFEO Accompaniment Program?

Beside the Pleiades (PHR) and Cosmo-Skymed (CSK) systems developments forming ORFEO, the dual and bilateral system (France - Italy) for Earth Observation, the ORFEO Accompaniment Program was set up, to prepare, accompany and promote the use and the exploitation of the images derived from these sensors.

The creation of a preparatory program is needed because of :

- the new capabilities and performances of the ORFEO systems (optical and radar high resolution, access capability, data quality, possibility to acquire simultaneously in optic and radar),

- the implied need of new methodological developments : new processing methods, or adaptation of existing methods,
- the need to realize those new developments in very close cooperation with the final users, the integration of new products in their systems.

This program was initiated by CNES mid-2003 and will last until mid 2013. It consists in two parts, between which it is necessary to keep a strong interaction:

- A Methodological part,
- A Thematic part.

This Accompaniment Program uses simulated data (acquired during airborne campaigns) and satellite images quite similar to Pleiades (as QuickBird and Ikonos), used in a communal way on a set of special sites. The validation of specified products and services will be realized with Pleiades data

Apart from the initial cooperation with Italy, the ORFEO Accompaniment Program enlarged to Belgium, with integration of Belgian experts in the different WG as well as a participation to the methodological part.

Where can I get more information about the ORFEO Accompaniment Program?

Go to the following web site: `http://smsc.cnes.fr/PLEIADES/A_prog_accomp.htm`.

31.1.4 Who is responsible for the OTB development?

The French Centre National d'Études Spatiales, CNES, initiated the ORFEO Toolbox and is responsible for the specification of the library. CNES funds the industrial development contracts and research contracts needed for the evolution of OTB.

31.2 License

31.2.1 Which is the OTB license?

OTB is distributed under a CeCILL free software license:
`http://www.cecill.info/licences/Licence_CeCILL_V2-en.html` which is recognized by the Free Software Foundation. It can be considered similar to the GNU GPL license.

31.2.2 If I write an application using OTB am I forced to distribute that application?

No. The license gives you the option to distribute your application if you want to. You do not have to exercise this option in the license.

31.2.3 If I write an application using OTB am I forced to contribute the code into the official repositories?

No. The CeCILL license impose only to distribute the source of the application to your users.

31.2.4 If I wanted to distribute an application using OTB what license would I need to use?

The CeCILL license or the GNU GPL license.

31.2.5 I am a commercial user. Is there any restriction on the use of OTB?

OTB can be used internally (”in-house”) without restriction, but only redistributed in other software that is under the CeCILL license. Moreover you need to distribute the source of your application to your users and only them.

31.3 Getting OTB

31.3.1 Who can download the OTB?

Anybody can download the OTB at no cost.

31.3.2 Where can I download the OTB?

Go to `http://www.orfeo-toolbox.org` and follow the ”download OTB” link. You will have access to the OTB source code, to the Software User’s Guide and to the Cookbook of the last release. Binary packages are also provided for the current version. OTB and Monteverdi are also integrated in OSGeo-Live since version 4.5. You can find more information about the project at `http://live.osgeo.org/`. Moreover you can found the last release of Monteverdi and OTB applications through the OSGeo4W installer.

31.3.3 How to get the latest bleeding-edge version?

You can get the current development version, as our repository is public, using Mercurial (available at `http://www.selenic.com/mercurial`). Be aware that, even if the golden rule is *what is committed will compile*, this is not always the case. Changes are usually more than ten per day.

The first time, you can get the source code using:

```
hg clone http://hg.orfeo-toolbox.org/OTB
```

Then you can build OTB as usual using this directory as the source (refer to build instructions).

Later if you want to update your source, from the OTB source directory, just do:

```
hg pull -u
```

A simple `make` in your OTB binary directory will be enough to update the library (recompiling only the necessary stuff).

31.4 Special issues about compiling OTB from source

All information about OTB compilation can be found into the related section. We present here only the special issues which can be encountered.

Debian Linux / Ubuntu

On some Debian and Ubuntu versions, the system GDAL library and its tiff internal symbol might conflict with the system Tiff library (bugs.debian.org/558733). This is most likely the case if you get odd segmentation fault whenever trying to open a tiff image. This symbol clash happens when using OTB. A workaround to the issue has been provided in GDAL sources, but is available in the 1.9.0 release.

The recommended procedure is to get this recent source and build GDAL from sources, with the following configure command:

```
./configure --prefix=INSTALL_DIR --with-libtiff=internal
            --with-geotiff=internal
            --with-rename-internal-libtiff-symbols=yes
            --with-rename-internal-libgeotiff-symbol
```

Errors when compiling internal libkml

The internal version of libkml cannot be compiled when using an external build of ITK. See `http://bugs.orfeo-toolbox.org/view.php?id=879` for more details.

To workaround the problem, either use an external build of libkml (it is provided on most systems), or use an internal build of ITK by setting to OFF the CMake variable OTB_USE_EXTERNAL_ITK.

OTB compilation and Windows platform

To build OTB on Windows, we highly recommend using OSGeo4W which provides all the necessary dependencies.

Currently it is not possible to build OTB in Debug when using the dependencies provided by OSGeo4W. If you want to build OTB in Debug for Windows, you will need to build and install manually each dependency needed by OTB. You should use the same compiler for all the dependencies, as much as possible.

Therefore, we highly recommend you to use OSGeo4W shell environment to build OTB. You can use the 32 or 64 bit installer, since OSGeo4W provides all the necessary dependencies in the two cases. Please follow carefully the procedure provided in the Software Guide.

Typically, when using the dependencies provided by OSGeo4W, compile OTB in Release or RelWithDebInfo mode.

31.5 Using OTB

31.5.1 Where to start ?

OTB presents a large set of features and it is not always easy to start using it. After the installation, you can proceed to the tutorials (in the Software Guide). This should give you a quick overview of the possibilities of OTB and will teach you how to build your own programs. You can also found some information in the OTB Cookbook in which we provide some recipes about remote sensing with OTB.

31.5.2 What is the image size limitation of OTB ?

The maximum physical space a user can allocate depends on her platform. Therefore, image allocation in OTB is restricted by image dimension, size, pixel type and number of bands.

Fortunately, thanks to the streaming mechanism implemented within OTB's pipeline (actually ITK's), this limitation can be bypassed. The use of the `otb::ImageFileWriter` at the end of

the pipeline, will seamlessly break the large, problematic data into small pieces whose allocation is possible. These pieces are processed one after the other, so that there is not allocation problem anymore. We are often working with images of 25000×25000 pixels.

For the streaming to work, all the filters in the pipeline must be streaming capable (this is the case for most of the filters in OTB). The output image format also need to be streamable (not PNG or JPEG, but TIFF or ENVI formats, for instance).

The class `otb::ImageFileWriter` manage the steaming process following two strategies: by tile or by strip. Different size configuration for these two strategies are available into the interface. The default mode use the information about how the file is streamed on the disk and will try to minimize the memory consumption along the pipeline. More information can be found into the documentation of the class.

31.6 Getting help

31.6.1 Is there any mailing list?

Yes. There is a discussion group at `http://groups.google.com/group/otb-users/` where you can get help on the set up and the use of OTB.

31.6.2 Which is the main source of documentation?

The main source of documentation is the OTB Software Guide which can be downloaded at `http://www.orfeo-toolbox.org/packages/OTBSoftwareGuide.pdf`. It contains tenths of commented examples and a tutorial which should be a good starting point for any new OTB user. The code source for these examples is distributed with the toolbox. Another information source is the on-line API documentation which is available at `http://www.orfeo-toolbox.org/doxygen`.

You can also find some information about how to use Monteverdi, Monteverdi2 and the OTB-Applications into the Cookbook at `http://www.orfeo-toolbox.org/CookBook/`.

31.7 Contributing to OTB

31.7.1 I want to contribute to OTB, where to begin?

There are many ways to join us in the OTB adventure. The more people contribute, the better the library is for everybody!

First, you can send an email to the user mailing list (otb-users@googlegroups.com) to let us know what functionality you would like to introduce in OTB. If the functionality seems important for the

OTB users, we will then discuss on how to retrieve your code, make the necessary adaptions, check with you that the results are correct and finally include it in the next release.

You can also run the nightly tests so we have a wider range of platforms to detect bugs earlier. Look at section 31.8.

You can also find more information about how to contribute at `http://orfeo-toolbox.org/otb/contribute.html`

31.7.2 What are the benefits of contributing to OTB?

Besides the satisfaction of contributing to an open source project, we will include the references to relevant papers in the software guide. Having algorithms published in the form of reproducible research helps science move faster and encourages people who needs your algorithms to use them.

You will also benefit from the strengths of OTB: multi-platform, streaming and threading, etc.

31.7.3 What functionality can I contribute?

All functionalities which are useful for remote sensing data are of interest. As OTB is a library, it should be generic algorithms: change, detection, fusion, object detection, segmentation, interpolation, etc.

More specific applications can be contributed using the framework directly in the Applications directory of OTB.

31.8 Running the tests

31.8.1 What are the tests?

OTB is an ever changing library, it is quite active and have scores of changes per day from different people. It would be a headache to make sure that the brand new improvement that you introduced didn't break anything, if we didn't have automated tests. You also have to take into account differences in OS, compilers, options, versions of external libraries, etc. By running the tests and submitting it to the dashboard, you will help us detect problems and fix them early.

For each class, at minimum there is a test which tries to instantiate it and another one which uses the class. The output of each test (image, text file, binary file) is controlled against a baseline to make sure that the result hasn't changed.

All OTB tests source code are available in the directory `Testing` and are also good examples on how to use the different classes.

31.8.2 How to run the tests?

There is more than 2500 tests for OTB and it takes from 20 minutes to 3 hours to run all the test, mainly depending on your compilation options (Release mode does make a difference) and of course your hardware.

To run the tests, you first have to make sure that you set the option `BUILD_TESTING` to `ON` before building the library. If you want to modify it, just rerun ccmake, change the option, then make.

For some of the tests, you also need the test data and the baselines (see 31.8.3).

Once OTB is built with the tests, you just have to go to the binary directory where you built OTB and run `ctest -N` to have a list of all the tests. Just using `ctest` will run all the tests. To select a subset, you can do `ctest -R Kml` to run all tests related to kml files or `ctest -I 1,10` to run tests from 1 to 10.

31.8.3 How to get the test data?

Data used for the tests are also versioned using Mercurial (see 31.3.3).

You can get the base doing:

```
hg clone http://hg.orfeo-toolbox.org/OTB-Data
```

This is about 1 GB of data, so it will take a while, but you have to do it only once, as after, a simple

```
hg pull -u
```

will update you to the latest version of the repository.

You can also easily synchronize the directory you retrieve between different computers on your network, so you don't have to get it several times from the main server. Check out Mercurial capabilities.

31.8.4 How to submit the results?

Once you know how to run the tests, you can also help us to detect the bugs or configuration problems specific to your configuration. As mentioned before, the possible combinations between OS, compiler, options, external libraries version is too big to be tested completely, but the more the better.

You just have to launch ctest with the `-D Experimental` switch. Hence:

```
ctest -D Experimental -A CMakeCache.txt
```

And you will be able to see the result at

`http://dash.orfeo-toolbox.org/Dashboard/index.php?project=OTB`.

If you are interested in setting up a nightly test (automatically launched every night), please contact us and we will give you the details.

31.9 OTB's Roadmap

31.9.1 Which will be the next version of OTB?

OTB's version numbers have 3 digits. The first one is for major versions, the second one is for minor versions and the last one is for bugfixes.

The first version was 1.0.0 in July 2006. Version 1.2.0, 1.4.0 and 1.6.0 were released in between. The 2.0.0 major version was released in December 2007. The 2.2.0, 2.4.0 and 2.6.0 (*Halloween*) in June, July and November 2008 respectively. The 2.8.0 (*Gong Xi Fa Cai*) came out in January 2009, the 3.0.0 (*Manhã de Carnaval*) in May 2009, the 3.2.0 (*62°38′35″S 60°14′31″W*) in January 2010, the 3.4.0 (*Perl A Rebours*) in July 2010, the 3.6.0 (*California Dreamin'*) in October 2010, the 3.8.0 (*Pack Ice*) in December 2010, the 3.10.0 (*Feliç aniversari*) in June 2011, the 3.12.0 (Πλελαεζ) in February 2012, the 3.14.0 (*Happy*) in July 2012, the 3.14.1 in October 2012, the 3.16 () in February 2013 , the 3.18 (*Seven years of Coding*) in July 2013, the 3.18.1 in July 2013 and the 3.20 in November 2013 (... *(and one more for the road)*).

The current one is 4.0.0.

What is a major version?

A major version of the library implies the addition of high-level functionalities as for instance image registration, object recognition, etc.

What is a minor version?

A minor version is released when low-level functionalities are available within one major functionality, as for instance a new change detector, a new feature extractor, etc.

What is a bugfix version?

A bugfix version is released when significant bugs are identified and fixed.

31.9.2 When will the next version of OTB be available?

We plan to release two major new OTB version once a year. You can find some information into the roadmap section of the wiki

31.9.3 What features will the OTB include and when?

There is no detailed plan about the availability of OTB new features, since OTB's content depends on ongoing research work and on feedback from thematic users of the ORFEO Accompaniment Program.

Nevertheless, the main milestones for the OTB development are the following:

- Version 1 (2006):
  - core of the system,
  - IO,
  - basic filtering, segmentation and classification,
  - basic feature extraction,
  - basic change detection.
- Version 2 (2007):
  - geometric corrections,
  - radiometric corrections,
  - registration.
- Version 3 (2009):
  - multi-scale and multi-resolution analysis,
  - object detection and recognition,
  - supervised learning.
- Version 3.X (2010-14):
  - data fusion,
  - spatial reasoning,
  - hyperspectral images analysis,
  - large scale segmentation,
  - stereo reconstruction
  - ...

- Version 4.X (2014 and later):
  - support of ITK 4.X (internal or external)
  - Clean up: migration of FLTK related code from OTB to Monteverdi, remove support for pqxx, gettext and LibLAS.

You can find more information in the RELEASE_NOTES.txt.

CHAPTER

THIRTYTWO

RELEASE NOTES

```
OTB-v.4.0.0 - Changes since version 3.20 (2013/03/13)
------------------------------------------------------

* Library:

  * Core:
    * [Breaking change !] Change OTB implementation and API to support ITK version 4.5
      * More information at http://wiki.orfeo-toolbox.org/index.php/Migration_guide_OTBv4
    * Refactor otbAttributesMapOpeningLabelMapFilter to be compatible with ITK 4.5
    * Remove FLTK based Visualization part from OTB: all these projects are now in Montev
    * Rename EuclideanDistance as EuclideanDistanceMetric
    * Remove otbMaskedScalarImageToGreyLevelCoocurenceMatrixGenerator
    * Use local masks in otbHaralickTexturesImageFunction
    * Remove methods of otbSystem.h which can be replaced by similar ones in itksys/Syste
    * Move classes about Amplitude and Phase functors from visualization to basic filter
    * otbImageToLabelMapWithAttributesFilter inherits from itkImageToImageFilter instead
    * Overload GenerateInputRequestedRegion in otbImageToLabelMapWithAttributesFilter
    * Override VerifyInputInformation in otbImportGeoInformationImageFilter
    * Adding a gamma parameter in VectorRescaleIntensityImageFilter to allow for gamma c
    * Clean up JoinHistogramMI code
    * Fix race condition in BinaryFunctorNeighborhoodJoinHistogramImageFilter
    * Remove unused OTB_USE_SYSTEM_VXL and OTB_VXL_DIR from OTBConfig and UseOTB
    * Improve detection of Large Files Support by not unconditionnally defining LFS rela
    * Support for Visual Studio 2012
    * Support for Visual Studio 2013
    * Support compilation in MacOSX 10.9 with latest XCode
    * Support for clang 3.5

  * Testing:
    * Correct multibaseline support
```

```
    * Move test related to amplitude and phase functor from visualization to basic filters

  * CMake:
    * Use modern CMake style: no block-end arguments and all CMake command to lower case format

  * ThirdParties:
    * OTB support now ITK with version greater to 4.5.0 (internal and external)
    * Remove FLTK dependency
    * Remove GETTEXT dependency
    * Remove LIBLAS dependency
    * Remove PQXX dependency
    * Improve support of muparser 2.0
    * Deactivate the possibility offered by CURL to download multiple files in parallel
    * Support mapnik 2.2

* Applications:

  * Updated applications:
    * ColorMapping : Remove dependency of ColorMapping to Visualization class
    * Convert : Adding gamma correction method the convert application
    * HomologousPointsExtraction : add mode.geobins.binsizey and mode.geobins.binstepy to allow
    * HomologousPointsExtraction : new mode.geobins.margin parameter to only search inside image

  * Core framework:
    * Improve the support of XML parameters input/output file
    * Improve the input VectorData/Image/Filename parameter to give access to m_Input attribute

* Monteverdi:
    * Support OTB-ITKv4 API
    * Integrate FLTK visualization framework into Monteverdi from OTB and offers the possiblitit
    * Support of MacOSX 10.9 compilation
    * Improve support of Windows platform for otbViewer
    * Remove intertionalisation test from Monteverdi

* Bugs fixed:
  * OTB-applications:
    * 0000884: InputImage parameter in java wrappers didn't overload the input parameters provid
    * 0000883: InputImageList parameter in pyhton wrappers didn't overload the input parameters
    * 0000873: BandMath application in gui mode "Save to xml" option doesn't save "exp" paramete
    * 0000836: Error in Exact Large-Scale Mean-Shift segmentation, step 2
    * 0000824: otbgui_Orthorectification : changing the input image does not update UTM paramete
    * 0000881: GenerateRPCSensorModel application generate stats file with wrong elevation value
```

```
  * OTB-lib:
    * 0000878: apTvDmStereoFramework fails with muParser 2.2
    * 0000850: apTvDmBlockMatchingTest Parser error Unexpected token if
    * 0000862: Cannot build OTB with mapnik 2.2
    * 0000858: cannot build otb tests with ITK trunk
    * 0000851: Build error on test 0000169-fftcomplextocomplex
    * 0000861: CMake detects mapnik 2.2.0 as mapnik 0.7
    * 0000859: Unable to compile OTB trunk with external ITK trunk

  * Orfeo Toolbox (OTB):
    * 0000849: otbgui applications scrambled file names
    * 0000863: ConvertSensorToGeoPoint  application in GUI mode execute button is not ac
    * 0000872: Internal ITK 4.4.2 and ITK 4.5.0 source codes are mixed together in the O
    * 0000864: MultiResolutionPyramid MTV2 is in an endless loop of generation if the pa
    * 0000830: otb::PolyLineImageConstIterator returns reference to temporary variable
    * 0000823: problem with python wrapper for otbApplication 'rasterization'

  * Documentation:
    * 0000838: ITK classes disappeared from doxygen during migration to ITK 4.x

OTB-v.3.20 - Changes since version 3.18.1 (2013/11/13)
------------------------------------------------------

* Library

  * Core
    * Fix trapezoidal function in otb::FuzzyVariable
    * PleiadesImageMetadataInterface
      * update calibration absolute gains for Pleiades (values provided by CNES and not
      * add calibration data for Pleiades 1B
    * StreamingStatisticsMapFromLabelImageFilter : change accumulator type to double ins
    * DEMHandler : support GeoTIFF as elevation
    * GenericRSResampleImageFilter & StreamingResampleImageFilter
      * add accessors for number of thread of deformation filter
      * set number of threads to 1 by default for the deformation field generator
    * SpotImageMetadataInterface : add relative spectral response for HRG1
    * MeanShiftSmoothingImageFilter : add range bandwidth parameter to adapt spectral ra
    * StreamingStatisticsVectorImageFilter : protect against corner cases when image has

  * ThirdParties
    * Synced ossim plugins with the ossim repository

* Applications
```

```
  * New applications :
    * Large scale MeanShift set of applications : LSMSSegmentation, LSMSSmallRegionMerging, LSMS
      * See recipe in the CookBook

  * Updated applications :
    * ClassificationMapRegularization : handle images with label up to 65535
    * DimensionnalityReduction : added new parameter for saving transformation matrix
    * DownloadSRTMTiles : support projected input images
    * MeanShiftSmoothing : expose range bandwidth parameter
    * StereoFramework : deformation field are computed in float precision instead of double
    * TrainImageClassifier : fix ordering confusion matrix in case of arbitrary labels, like in
    * DimensionnalityReduction : add bounds for number of components depending on input image

  * Core framework :
    * Fix otbgui_XXX scripts to check for existence of otbgui.sh
    * Support saving and loading application parameters from/to XML files
    * Support extended filename for complex input images
    * QtWidgetModel emits a signal with associated exception in case an error occurs during appl

* Bugs fixed :
  * OTB library
    * 0000805: All links in html FAQ return Error 404
    * 0000776: computeImagesStatistics imagelist input confusing error
    * 0000804: str and int concatenate error in Python Wrapper Application.GetParameterValue
    * 0000775: DoUpdateGUI() doing nothing for some parameters in QtWidget Wrapper
    * 0000799: when using OTB Applications in graphic mode "Execute" button become clickable eve
    * 0000801: Some mandatory parameter with RoleOutput  should not be set by user
    * 0000770: Output parameter does not appear anymore in the command line helper
    * 0000798: All the OTB app parameters are not all saved into the xml output file
    * 0000779: [OTB]otbTrainImagesClassifier generates an output *.CSV confusion matrix with a w
    * 0000809: LSMS Vectorization application didn't support ouput file with "-" special charact
    * 0000807: otbKmzExport application generate weird kmz if the tilesize parameter is equal to
    * 0000808: otbDownloadSRTMTiles application seems to be broken
    * 0000803: otbApplicationLauncherCommandLine -inxml parameter does not retrieve pixel type f
    * 0000794: Tiling mechanism didn't work into Large Scale MeanShift  application
    * 0000760: ClassificationMapRegularization output pixel values are always on 8 bits
    * 0000809: LSMS Vectorization application didn't support ouput file with "-" special charact
    * 0000803: otbApplicationLauncherCommandLine -inxml parameter does not retrieve pixel type f
    * 0000736: Error setting the index in RadiometricIndices application via python
    * 0000800: Watershed mode of segmentation application produce an image without CRS even if t
    * 0000806: Orthorectifcation application return black or weird output if we request an outpu
    * 0000755: otb-bin-qt 3.18.1 package on Ubuntu installation triggered a warning at installat
```

```
    * 0000801: Some mandatory parameter with RoleOutput should not be set by user
    * 0000770: Output parameter does not appear anymore in the command line helper
    * 0000793: Using dimensionality Reduction application with MAF algorithm and "Inverse
    * 0000773: [OTB]otbStreamingStatisticsMapFromLabelImageFilter wrongly counts and acc
    * 0000398: OTB does not handle ortho-ready products properly

  * Monteverdi2
    * 0000789: Crash when selecting badly imported dataset.
    * 0000787: Can't drag up in Quick look view with ortho product
    * 0000750: Importation of a dataset which didn't exist because otb-app didn't run
    * 0000791: Accuracy error when converting float (-4.31608963) to string.
    * 0000792: Checking "Load otb application from xml file" crashes monteverdi2 on any
    * 0000785: ITK exception raised when/after importing lena512color.jp2
    * 0000754: VertexComponentAnalysis app output importing leads to mvd2 crash
    * 0000756: BandMath application does not get ready when adding multiple inputs
    * 0000777: Wrong cartographic coordinates in pixel description widget for geotif pro
    * 0000749: Output of the applications are detected as inconsistent
    * 0000752: When we run a otb app the selection of the dataset into the database mana
    * 0000748: Drag and drop a dataset into a inputImageList widget of an otb-app didn't
    * 0000747: Drag and drop an image into MVD2 didn't work with Win platform
    * 0000746: Locked/unlocked button didn't work
    * 0000768: Monteverdi 0.5.0 package depend now on QWT
    * 0000790: Monteverdi 2 crashes when running segmentation

OTB-v.3.18.1 - Changes since version 3.18.0 (2013/07/22)
---------------------------------------------------------

* Library
  * Core and Third Parties
    * Update the JPEG2000ImageIO to decrease cache consumption and avoid memory leak bet
    * Improve the control over the generation of GDAL overviews with a new method to set

  * CMake
    * remove OTBParseArguments from OTB source because it is not used

  * Examples
    * Update HelloWorld example CMakeLists

  * Applications
    * Updated applications
      * Update Stereo application documentation example with new parameters
      * Add a log message about color mapping method used by application
    * Core Framework
```

```
      * Intialize properly QtWidgetChoiceParameter
    * Increase minimun cmake version to 2.8.3 wwhen build applications

OTB-v.3.18 - Changes since version 3.16 (2013/07/05)
----------------------------------------------------

Among the classical improvements and bug fixes to exisiting functionnalities, this release provi
the following main functionnalities :
 * Huge improvements in Stereo framework, to compute DEM from stereo pairs :
   check the StereoFramework application !
 * Whole new classification framework, with seamless integration of all OpenCV classifiers in ad
   existing libSVM classifier, kept for backward compatibility : check the TrainImageClassifier
 * A classifiers fusion framework based on Dempster Shafer theory : check the FusionOfClassifica

The full list of improvements comes here :

* Library
  * Core and Third Parties
    * Expose Curl timeout as parameter
    * OGRLayerStreamStitchingFilter : fix issue #610 'Attempt to delete shape with feature id (4
    * Preparation for ITKv4 : got rid of most patches in internal ITK version
    * Removal of old deprecated methods in all OTB classes
    * Fix mangling of internal OpenJPEG
    * Simpler and more automatic configuration and build on Windows based on OSGeo4W

  * Basic filters
    * Add NoData value and flag for StreamingMinMaxVectorImageFilter
    * StreamingStatisticsImageFilter & StreamingStatisticsVectorImageFilter : support for skippi

  * Stereo
    * New classes :
      * DisparityMapTo3DFilter : convert disparity map in epipolar geometry to 3D image in epipo
      * MultiDisparityMapTo3DFilter : convert several disparity maps in sensor geometry to a 3D
      * LineOfSightOptimizer : algorithm to fuse several elevation values by line of sight optim
      * BijectionCoherencyFilter : from 2 disparity maps, compute coherency left-right and right
      * Multi3DToDEMFilter : fuse several 3D images to produce an elevation map
      * DisparityTranslateFilter : filter to translate epipolar disparities into sensor disparit
    * PixelWiseBlockMatchingImageFilter : fix initialisation of metric and disparities
    * PixelWiseBlockMatchingImageFilter : supports a shift on the subsampled grid
    * SubPixelDisparityImageFilter : supports a subsampled grid (with shift)
    * PixelWiseBlockMatchingImageFilter & SubPixelDisparityImageFilter : subsampled disparities

  * IO
```

```
  * GDALImageIO : support reading overviews. "image.tif?&resol=3" is now supported as
  * Extended file names now supports the "box" key for writing only a subset of the ima

* Learning
  * Generic framework of classification filters, integrating OpenCV classifiers and lib
    * New classes
      * MachineLearningModel
      * MachineLearningModelFactory
      * LibSVMMachineLearningModel, based on pre exsiting libsvm functionnalities
      * OpenCV based classifiers :
          BoostMachineLearningModel DecisionTreeMachineLearningModel GradientBoostedTre
          KNearestNeighborsMachineLearningModel NeuralNetworkMachineLearningModel
          NormalBayesMachineLearningModel RandomForestsMachineLearningModel SVMMachineL

  * ConfusionMatrixCalculator : add correspondence between class label and indices
  * ConfusionMatrixMeasurements : add new class for computation of precision, recall a

* Fuzzy
  * New Dempster Shafer based fusion of classifiers framework
    * Theory explained in http://wiki.orfeo-toolbox.org/index.php/Information_fusion_f
    * New classes : DSFusionOfClassifiersImageFilter, ConfusionMatrixToMassOfBelief

* Segmentation
  * Fix some numerical instabilities in mean shift segmentation filter

* Radiometry
  * Fix spectral sensitivity reading of Pleiades images
  * Add PHR 1B averaged solar irradiance provided by CNES


* Applications
  * New applications
    * Added new SRTM tiles downloader (DownloadSRTMTiles)
    * Added new PLY file generator (GeneratePlyFile)
    * TrainImageClassifier and ImageClassifier : made TrainSVMImageClassifier & ImageSV
      more generic and expose OpenCV classifiers.
      Check the migration guide at : http://wiki.orfeo-toolbox.org/index.php/Classifica

  * Updated applications
    * StereoFramework :
      * Handles several images in input by stereo couples
      * More robust block matching with coherency checking in both directions
      * Choice of metric for block matching
```

```
        * Optional median filtering for disparities
        * Add variance threshold on input images for masking pixels where variance is too low
        * Add support for final projection of DEM in other SRS than WGS84
      * ExtractROI : add a mode to fit another reference image
      * StereoRectificationGridGenerator : disable agvdem by default
      * StereoSensorModelToElevationMap application removed to avoid duplicating functionnalitie
      * MaxiumuAutocorrelationFactor application removed to avoid duplicating functionnalities p
      * BlockMatching : expose step parameter
      * BlockMatching : supports a shift on the subsampled grid
      * ColorMapping : remove flooding of logs
      * TrainImageClassifier & ComputeConfusionMatrix : enhance reporting of confusion matrix by
      * ReadImageInfo : add index of largest possible region
      * ComputeImageStatistics : support for background values, add progress reporting
      * CompareImages : use whole image when no ROI is provided
      * RigidTransformResample : all transformations are now synced to be from input space to ou

    * Core Framework
      * Manage UTF8 paths in GUI
      * Fix a crash in string list parameter widget in GUI

* Monteverdi

* Bug Fixes
  * OTB-lib
    * 0000707: Memory leaks in ApplicationWrappers
    * 0000712: weird result of DempsterShaffer fusion of classification
    * 0000685: UTF-8 paths not managed by Qt GUI in OTB Applications
    * 0000686: Input file paths are deleted in some input fields of Qt GUIs
    * 0000684: Impromptu cursor jumps in some input fields of Qt GUIs

  * Documentation
    * 0000643: Installation documentation is outdated
    * 0000720: [OTB Wiki] Unable to save an edited page with a hypertext link within it

  * OTB-applications
    * 0000704: results of otbcli_Segmentation reflexed
    * 0000711: Segmentation Fault and crash of applications after modifying any input  "Paramete
    * 0000709: otbcli_ComputeImagesStatistics includes NaNs and background values
    * 0000710: otbcli_ComputeImagesStatistics "progress" switch doesn't work
    * 0000697: ComputeConfusionMatrix
    * 0000670: Confusion matrix report unclear
    * 0000723: CompareImage application without ROI parameter results in FATAL error
```

```
  * Monteverdi2
    * 0000632: Monteverdi2 crashes after zooming twice
    * 0000714: Import existing image in the database leads to a crash
    * 0000675: Filename too long
    * 0000708: MVD2 - Cache-dir removed from disk.
    * 0000664: Very long loading time the second time with TIFF product
    * 0000655: ProgressDialog does not close if error is displayed.
    * 0000646: Viewport is black or diminish when maximising or resizing the window befo
    * 0000645: Viewport goes black or diminish when maximising or resizing the window af
    * 0000639: Using keyboard arrows with Monteverdi2 maximized grabs all keyboards even
    * 0000653: "monteverdi2 imagepath" creates a dataset model directory even if the ima
    * 0000699: Datasets loaded through mvd2-viewer command-line are disabled
    * 0000679: Inconsistency between mouse cursor position and image displacement when d
    * 0000669: The application don't detect the fact that I didn't modify the settings
    * 0000668: Precision loss when loading/saving/reloading
    * 0000666: upper quantile is not set to 0.0 on integer image type, when using min/ma
    * 0000656: Import Windows does not close
    * 0000659: At first startup, 'mvd2' dir is not created but Monteverdi2 shoudl create
    * 0000660: Wrong display settings saved
    * 0000657: Radiometry values hide WGS84 coordinates in status bar
    * 0000654: When minimzing the window, all widgets are closed
    * 0000665: Monteverdi2-0.1 label in Startup menu does not have an icon
    * 0000644: Make Monteverdi2 window autofit to the screen's size
    * 0000638: Displacement in the image let a black line of pixels at the top of the fu
    * 0000636: Displacement related to keyboard arrows is to small
    * 0000637: Displacements associated with vertical keyboard arrows are inverted with
    * 0000633: Can not edit spinner fields in Video Color Dynamics widget
    * 0000634: Steps of Quantiles spin-box are to coarse
    * 0000718: Confirm dialog only displays MD5 name when deleting dataset.
    * 0000648: Deploy icons for Monteverdi2 in  packages and also for local build if pos

OTB-v.3.16 - Changes since version 3.14.1 (2013/02/04)
------------------------------------------------------

* Library
  * Core and Third Parties
    * Various enhancement of PleiadesImageMetadataInterface
    * Added GetEnhancedBandNames method in ImageMetadataInterface
    * Added read and write geom file support in OssimSensorModelAdapter
    * Refactoring of DEMHandler:
      * Turned the class into singleton
      * Made the DEMHandler the single configuration point for all elevation setup
      * Deprecated all methods from other classes allowing to configure elevation source
      * Added Exhaustive testing of all configuration cases (DEM, geoid, default)
```

```
    * Improved documentation
  * Refactoring of SensorModelAdapter:
    * Decreased size of the code
    * Made methods stick to what OSSIM does
  * Refactored RpcProjectionAdapter into RpcSolverAdapter
  * Updated ossim to r21971

* IO
  * Added support for GDAL driver creation options in GDALImageIO
  * Added support for external geom files in ImageFileReader
  * Extended filenames
    * Added framework for extended filenames (see http://wiki.orfeo-toolbox.org/index.php/Exte
    * Added support for extended filenames in ImageFileReader
    * Added support for extended filenames in ImageFileWriter
  * Refactored StreamingImageFileWriter and ImageFileWriter
    * ImageFileWriter is now the only class to use
    * StreamingImageFileWriter is a deprecated subclass provided for backward compatibility
    * Fixed a bug when the largest possible region could be asked in some cases

* Projections
  * Refactored the GCPsToSensorModel filter

* BasicFilters
  * Simplified computation of coefficients in Frost and Lee filters

* Fusion
  * Added the LMVM fusion algorithm (kindly contributed by A. Tzotsos)

* Radiometry
  * Updated solar irradiance for WV2 (kindly contributed by D. Duros)
  * Enhanced the TOA radiance computation for WV2 by integrating the effective bandwidth

* Learning
  * Improved ListSample generation
    * Added support for interior rings
    * Fixed support for class mininum size
  * Added a filter for classification map regularization by majority voting

* Segmentation
  * Added segmentation algorithm based on multiscale morphological structures classification

* OBIA
  * Added a filter to compute mean radiometric values for each segment of a labeled image
```

```
  * Visualization
    * Added a method to change RegionGlComponent color in ImageView
    * Moved layer description in a single place

  * Applications
    * Framework
      * Modified the elevation parameters handling to be consistent with refactoring

    * New Applications
      * Added new radiometric indices application (RadiometricIndices)
      * Added new haralick and structural feature set texture extraction application (Ha
      * Added new morphological operation applications (BinaryMorphologicalOperation,Gra
      * Added new local statistics extraction applications (LocalStatisticsExtraction)
      * Added new edge extraction application (EdgeExtraction)
      * Added new homologous points extraction application, including large scale extrac
      * Added new application to refine a sensor model from a geom file and a set of tie
      * Added new pan-sharpening application with 3 different algorithms (PanSharpening)
      * Added new classification maps fusion application (FusionOfClassifications)
      * Added new classification map regularization application (ClassificationMapRegula
      * Added new confusion matrix computation application (ComputeConfusionMatrix)
      * Added new tile fusion application (TileFusion)
      * Added new end-to-end stereo pair to Digital Surface Model application (StereoFra

    * Miscellanous
      * Added an optional clamp in OpticalCalibration application output
      * Added segmentation algorithm based on multiscale morphological structures classi
      * Added an optional output to the ReadImageInfo application to write the keyword l
      * Added support for large image in image mode of ColorMapping application
      * Added support for histogram clamping settings and mask input in Convert applicat
      * Added support for UTM zone and hemisphere estimation by default in OrthoRectifica

* Monteverdi
  * Refactored to fit the new elevation configuration method
  * Added Support for extended filenames

* Bug fixes
 * OTB-Packaging
    * 0000591: Remove "homemade" gdal from OTB PPAs

  * Orfeo Toolbox (OTB)
    * 0000608: Annoying GDAL warning about GCP in OTB writer
    * 0000619: Superimpose application can't deal with 2 ortho images
```

```
    * 0000622: Extended filename does not seem to be compatible with OTB applicatiosn (command l
    * 0000599: Optical calibration of DIMAPv1 PHR products
    * 0000601: PHR optical calibration : Band_Solar_Irradiance at 999 on some files
    * 0000618: MultiResolutionPyramid application can not handle relative output path
    * 0000617: Crash with StreamingStatisticsVectorImageFilter
    * 0000602: Geom file of extract of ortho PHR data are not loaded in the otbKeywordList
    * 0000600: Wrong band ordering in 3 Pleiades metadata (gain, bias, solar irradiance)
    * 0000629: Exception raised in otbcli_MaximumAutocorrelationFactor

  * OTB-applications
    * 0000616: otbcli_OpticalCalibration fails to read Worldview-2 metadata


OTB-v.3.14.1 - Changes since version 3.14.0 (2012/10/02)
---------------------------------------------------------

* Library
  * Support external FLTK 1.3 on windows
  * Simplify GDAL import during configuration
  * Remove ossim dependencies from aeronet file reader
  * Add adjacency effect in OpticalCalibration application
  * Improve Pleiades support :
    * TOA optical calibration available
    * Improve support of mega tiles products


* Monteverdi
  * Support of MacOSX 10.8

* Bug fixes :
  * OTB-lib
    * 0000577: Remove the need for both GDAL_CONFIG and GDALCONFIG_EXECUTABLE
    * 0000573: tiff error in ossim when we read big uncompress JPEG2000 with Pleiades Primary le
    * 0000552: Application GridBasedImageResampling doesn't behave properly outside the input gr
    * 0000576: ImageToPointSetFilter work only with PointSets of type DefaultStaticMeshTraits
    * 0000575: Not able to access SDS layers in HDF4 datasets using BandMath
    * 0000572: using Segmentation application with .kml vector output using input which is not i
    * 0000586: OTB does not compile with gcc 4.7 on some distros
    * 0000579: Can not use files with "--" in their names in applications
    * 0000556: Help parameters display output wrong MISSING parameters with application launched
    * 0000507: Java wrapper installation

  * Monteverdi
```

```
    * 0000570: SVM classification module works only with three bands images
    * 0000583: Weird spacing value for the Resampling module output
    * 0000581: Mean Shift Clustering Crash
    * 0000474: In TileMap Import module, search place by name does not work anymore
    * 0000529: Monteverdi fails to build using fltk 1.3 opensuse 12.1
    * 0000582: Save/Quit button in the Resampling module does not close the module
    * 0000571: Monteverdi crash in SVM Classification when trying to import SVM model tw

  * Documentation
    * 0000366: SG-html has 2 "bibliography"
    * 0000371: Generate_FAQ script needs updates
    * 0000367: Software Guide HTML : missing index.html
    * 0000372: clean up Cookbook generation logs


OTB-v.3.14.0 - Changes since version 3.12.0 (2012/07/09)
--------------------------------------------------------

* Library
  * New MeanShift implementation
    * Add MeanShiftSmoothingImageFilter class with threading support
    * Add MeanShiftKernels class
    * Add MeanShiftConnectedComponentSegmentationFilter class to
      concatenate MeanShift filter and connected component
    * Add MeanShiftSegmentationFilter which performs segmentation of an
      image by chaining a mean shift filter and region merging filter.
    * Move MeanShiftVectorImageFilterExample to
      MeanShiftSegmentationFilterExample
    * MeanShiftImageFilter and MeanShiftVectorImageFilter are now
      deprecated

  * OGR encapsulation for use in large-scale segmentation framework
    * Add a method converting a DataTree node to a list of OGRLayer*
    * Add OGRDataSourceWrapper, OGRDriversInit, OGRLayerWrapper,
      OGRFieldWrapper, OGRFeatureWrapper, OGRGeometryWrapper and OGR
      classes to encapsulate OGR in the otb namespace
    * Add GeometriesProjectionFilter, GeometriesSet, GeometriesSource and
      GeometriesToGeometriesFilter classes to encapsulate OGR Geometries
      projection
    * Add OGRHelpers class for easier conversion to OGR string
    * Add GeometriesProjectionFilter filter to
    * Add ImageReference, OGRGeometriesVisitor classes
```

```
* Large-scale Segmentation Framework (OBIA)
  * Create a new repository Segmentation
  * Add GdalDataTypeBridge
  * Add LabelImageToVectorDataFilter class
  * Add StreamingImageToOGRLayerSegmentationFilter class which allow
    stream segmentation and vectorization of the output label image
    (based on OGRWrappers)
  * Add LabelImageToOGRDataSourceFilter class to use GDALPolygonize
    method to transform a Label image into a OGRDataSource
  * Add PersistentImageToOGRDataFilter class. This class is a generic
    PersistentImageFilter, which encapsulate any filter which produces
    OGR data from an input Image
  * Add option 4Connected/8Connected for Polygonization in
    LabelImageToVectorDataFilter and LabelImageToOGRDataSourceFilter
  * Add OGRLayerStreamStitchingFilter class to make fusion of geometries
    in a layer (ogr) along streaming lines (based on OGRWrappers).
  * Add LabelImageRegionMergingFilter class
  * Add Example about OGRWrappers and HooverMetrics

* Pleiades Support
  * enhance support of PHR data with DIMAPv2 official root_tag
  * manage all cases from geotransform return by GDALJP2metadata
  * enhance support of PHR data with GML box and Sensor Model
  * Add TileImageFilter to support mosaic tiled images
  * Support of TIFF pleiades image and associated DIMAP metadata
  * upport for DIMAPv1 metadata format

* Stereo-rectification framework
  * Add StereorectificationDeformationFieldSource class
  * Add BlockMatchingImageFilter class for fast 2D block-matching
  * Add NCCBlockMatching functor
  * Add LPBlockMatching functor
  * Adding an optionnal geoid file, and the possibility to use height
    above ellispoid in DEMToImageGenerator
  * Add SubPixelDisparityImageFilter class to interpolate disparities
  * Add DisparityMapMedianFilter class
  * Add AdhesionCorrectionFilter class
  * Add DisparityMapToDEMFilter
  * Add example in DisparityMap/StereoReconstructionExample

* Miscellaneous
  * Modify otbImageLayer to enable the contrast stretch on full or
    zoom view in Monteverdi Viewer module
```

```
* Add RasterizeVectorDataFilter class
* Add VectorDataToLabelImageFilter for VectorData rasterization
  using an attribute to get the color for burning
* Add GDALDriverManagerWrapper class
* Add VectorDataEditVertexActionHandler class to allow user editing
  of vertex in vector data.
* Add VectorDataTranslateGeometryActionHandler class to handles the
  user action for geometries translation
* Add VectorDataEditionModel class for vertex edition and geometries
  translation
* Add a method to remove a specific geometry in the VectorData
* AddVectorData method always do notification, add a flag (set to
  true by default) to allow disabling it
* Enhance the support for Spot 1,2,3 metadata related to radiometry
* Add UnaryFunctorWithIndexWithOutputSizeImageFilter which implements
  neighborhood-wise generic operation on image
* Add WatershedSegmentationFilter composite filter to allow use of
  itk watershed inside large segmentation framework
* Add LabelImageRegionPruningFilter filter to merges regions in the
  input label image according to the input image of spectral values
  and the RangeBandwidth parameter.
* Rename VectorDataToImageFilter to VectorDataToMapFilter
* Move Hoover framework to Code/Segmentation
* Make RationalTransform inheriting from otb::Transform instead
  of itk::Transform
* Add Spacing and Origin to RationalTransform
* Fix bug in computation of NDBBBI for Spectral rule based classifier
* Remove deprecated classes :
  * QuickLookImageGenerator (replaced by StreamingShrinkImageFilter)
  * GeometricMomentImageFunction (unused)
* Improve removal of geometries in VectorDataEditionModel
* HistogramActionHandler : avoid changing positions outside viewed
  range
* PixelDescriptionModel : make the request for placename optional
  (lags when internet access is slow)
* PackedWidgetManager : add Shown method, add Resizable setter
* Patch internal muparser to avoid bugs with static storage varialbe
  deallocation in plugin context
* Modify MetaDataKey to avoid bugs with static storage varialbe
  deallocation in plugin context
* Enable KML writing using OGR (was previously done internally
  by libkml)
* GenericRSTransform can now be optimized using a set of tie-points,
```

```
    calling ossim internal sensor model refining implementation
  * PackedWidgetManager & SplittedWidgetManager : add method to set the
    label of each group
  * HistogramActionHandler : limit moves of asymptots with min/max of
    histogram
  * Curve2DWidget : add label support for each histogram
  * ImageToEnvelopeVectorDataFilter : support a sampling rate in pixels
    to be able to generate more than the four corners
  * GeoInformationConversion : add IsESRIValidWKT to test WKT for shp
    file support
  * OGRIOHelper : ensure OGR driver manager is initialized when we need it

* New Applications
  * Add PixelValue application
  * Add HooverCompareSegmentation application
  * Add GridBasedImageResampling application to perform grid-based
    image resampling
  * Add StereoRectificationGridGenerator application
  * Add RadiometricWaterIndices application
  * Add FineRegistration application for pixel-wise horizontal block
    matching
  * Add BlockMatching application
  * Add DimensionalityReduction application
  * Add LargeScaleSegmentation application
  * Add DisparityMapToElevationMap application
  * Add ComputeImageFeatures application
  * Add VectorDataReprojection application

* Misc. Applications
  * Add image origin to ReadImageInfoApplication
  * Use now InputFilenameParameter and OutputFilenameParameter instead
    of FilenameParameter
  * Use InputFilename and OuputFilename instead of Filename
  * New option in SVMClassifier application: sample.edg (non mandatory)
    to manage special cases with small samples
  * In KMeansClassification, Changing the random intialisation method
    since it can generate centroids that are too far from the image
    distribution and will never move
  * Add AddRANDParameter option in order to set mersenne twister seed
    for test reproducibility purpose
  * Display which key is wrong in a set of application parameters
  * Improve the help return by application
  * MeanShiftSegmentation application, which duplicates Segmentation
```

```
      application has been renamed to MeanShiftSmoothing application
    * Rasterization application rewritten to use the new
      OGRDataSourceToLabelImageFilter filter
        The application can rasterize in binary mode or burn the value of
        a specified field (similar to gdal_rasterize)
    * ColorMapping : fix settings of predefined colormap
    * ColorMapping : fix mode "method.image" in case image contains
      continuous labels
    * ImageEnveloppe : expose new sampling rate parameter
    * otbViewer improvements : add handling of HDF and JPEG2000 files
    * Remove custom Transmercator projection settings from application

* System
  * Added FLTK License
  * GDAL copyright notice removed because GDAL source code is not provided
    with OTB
  * OpenJPEG copyright file updated
  * Update internal Ossim to revision 20606
  * Support for Mapnik2
  * Make siftfast compilation optional (OTB_USE_SIFTFAST cmake option)
  * Support external tinyXML
  * Support external muparser
  * Support external libkml
  * Add a FindOSSIM.cmake to detect OSSIM easier
  * Update internal boost to 1.49.0
  * Suppress galib from OTB source tree (wasn't used)
  * Suppress KNN from OTB source tree (wasn't used)
  * Enhance/Add find_package support for OpenThread, Ossim, Expat, PQxx,
    Curl, GetText, ICUUC and LTDL
  * Install OTB-custom FindXXX.cmake files along with OTB, to be used
    from external projects
  * Make installation with OTB_WRAP_JAVA honor CMAKE_INSTALL_PREFIX
  * New compilers supported :
    * clang 3.2 (current development version)
    * gcc 4.6, 4.7, 4.8-dev
    * Intel icc

* Bug fixes :
  * OTB-lib
    * 0000532: OTB_SHOW_ALL_MSG_DEBUG option changes
               apTvClTrainSVMImagesClassifierQB456 test results
    * 0000568: Unable to compile OTB with a local version of the
               FFTW library
```

```
  * 0000531: Cannot compile OTB 3.12.0 with external FLTK 1.3
             on Windows
  * 0000564: ColorMapping application crash when using support
             image with input label image which contains holes in label
  * 0000563: Can not install OTB elsewhere than /usr/lib anymore
  * 0000557: Weird default value for RAM parameter in OTB application
  * 0000544: SWIG 2.0.5 not supported on mac
  * 0000554: OTB compilation : error while loading libfltk.so.9
  * 0000559: Even if OTB_USE_MAPNIK is ON, otbapp_Rasterization
             does not get compiled
  * 0000558: GetParameterFloat method of WrapperApplication
             class does not returns exactly input value
  * 0000550: BlockMatching application throws an exception
             when the "sub-pixel" mode is activated
  * 0000549: Error message related to boost_any_cast in
             StereoRectificationGridGenerator application
  * 0000547: MeanShiftFilter validation test is fialinf for
             Iteration and Spatial output
  * 0000542: Problem with win arch and testing
  * 0000521: Applications do not work anymore (Wrapper problem)
  * 0000522: otbApplicationLauncherQT is not reflecting
             the Disable/Enable state correctly
  * 0000511: Tags are repeated twice in Application, when using Qt framework

* Monteverdi
  * 0000555: monteverdi -in does not work with JP2 images
  * 0000560: Monteverdi compilation error
  * 0000527: While saving dataset with rescaling option,
             the channels nÂ° > 3 are incorrect

* OTB-applications
  * 0000518: Missing GDAL dependencies
  * 0000515: Space managing in command line
  * 0000510: OTB-Applications cannot compile when the sources
             are located in a directory with spaces in its name

* OTB-Packaging
  * 0000545: Issues with Monteverdi 1.10 binary
             applications on Mac OSX 10.6  (SL)
  * 0000525: Python not found during ubuntu package build
  * 0000526: Fix input of bfTvPolygonizationRasterization_WGS84

* Server administration
```

```
    * 0000519: Search button of current OTB doxygen documentation
               is broken
    * 0000523: Update doxygen version to get
               the same layout as the ITKv4 doxygen website

OTB-v.3.12.0 - Changes since version 3.10.0 (2011/01/31)
------------------------------------------------------------
* Library
  * MaximumAutocorrelationFactorImageFilter
  * MultivariateAlterationDetector
  * Add Hyperspectral processing filters
    * Dimensionnality estimation :
      * EigenValueLikelihoodMaximization
      * VirtualDimensionnality
    * Dimensionnality reduction :
      * PCAImageFilter - perform forward and inverse Principal Component
        Analysis decomposition
      * FastICAImageFilter - perform forward and inverse Independent
        Component Analysis decomposition, based on FastICA algorithm
      * MNFImageFilter - perform forward and inverse Maximum Noise
        Fraction decomposition
      * NAPCAImageFilter - perform forward and inverse Noise Adjusted
        Principal Component Analysis decomposition
    * Endmember extraction :
      * VcaImageFilter - performs Vertex Component Analysis
      * MDMDNMFImageFilter - performs Minimum Spectral Dispersion Maximum
        Spatial Dispersion nonnegative Matrix Factorization
    * Unmixing under Linear Mixture Model hypothesis :
      * UnConstrainedLeastSquareImageFilter - standard least square
        solving
      * NCLSUnmixingImageFilter - least square with non-negativity
        constraint
      * FCLSUnmixingImageFilter - least square with non-negativity and
        additivity constraint
      * ISRAUnmixingImageFilter - image space reconstruction algorithm
    * Anomaly detection :
      * LocalRxDetectorFilter
    * SparseUnMixingImageFilter : finds correlation in time series using
      sparse representation
    * Addition of several mathematical operations to support hyperspectral
      filters implementation
      * AngularProjectionImageFilter
      * AngularProjectionSetImageFilter
```

```
    * BinarySpectralAngleFunctor
    * ConcatenateScalarValueImageFilter
    * DotProductImageFilter
    * SparseWvltToAngleMapperListFilter
    * ProjectiveProjectionImageFilter
    * VectorImageToMatrixImageFilter
      Different sort of gradient filter for noise estimation in MNF :
    * LocalActivityImageFilter
    * LocalGradientImageFilter
    * HorizontalSobelVectorImageFilter
    * VerticalSobelVectorImageFilter
    * SobelVectorImageFilter
* Add Simulation module, based on Prospect and Sail
  * AtmosphericEffects
  * DataSpec5B
  * ImageSimulationMethod
  * LabelMapToSimulatedImageFilter
  * LabelToProsailParameters
  * LeafParameters
  * ReduceSpectralResponse
  * ReduceSpectralResponseClassifierRAndNIR
  * SailModel
  * SatelliteRSR
  * SpatialisationFilter
  * SurfaceReflectanceToReflectanceFilter
  * SpectralResponse
* Improve WaveletGenerator speed, and fix reconstruction issue is
  multithreaded environment
* ClampImageFilter, ClampVectorImageFilter
* ThresholdVectorImageFilter
* Support for writing PDS files (Planetary Data System) in
  ImageFileWriter, through GDALImageIO
* ImageRegionAdaptiveSplitter, RAMDrivenAdaptiveStreamingManager,
  New streaming strategy in writer, taking advantage of both tile size
  and pipeline memory print estimation
* Finer progress reporting in StreamingImageFileWriter
* Move ViewerManager application from OTB-Applications to OTB source
  tree, and rename as otbViewer
* Factor MsgReporter class in OTB source tree, and reuse it in
  Monteverdi
* HooverInstances, HooverConfusionMatrix : tools to evaluate a
  segmentation against a ground truth
* Removed deprecated class MapProjection
```

```
* Removed streaming and threading support from
  MeanShiftVectorImageFilter, since it was generating wrong labeled images
* Pleiades data support
  * Update to openjpeg rev 1111
  * Complete rework of JPEG2000ImageIO
    * Tile caching support
    * Multithreaded decoding
    * GMLBox decoding
    * Multi-resolution decoding support
  * Experimental Pleiades metadata support in ossimplugins :
    * RPC Sensor model
    * Calibration coefficient
    * Various information about the product
* New application module framework (BUILD_APPLICATIONS:BOOL=ON)
  * New library OTBApplicationEngine to generate application module
    as shared plugin objects
  * This replaces small command line utilities in OTB-Applications
  * Command line launcher for application module
  * Generic Qt based widget to show/configure/run an application
  * Qt based GUI application launcher
  * SWIG module on top of OTBApplicationEngine to execute applications
    from Python and Java
  * Quickstart scripts provided for launching the commandline tools
    (otbcli_XXX)
      and for starting the Qt GUI (otbgui_XXX)
  * The following applications are available in this release :
    * CartographicDBValidation
      * ComputePolylineFeatureFromImage
      * DSFuzzyModelEstimation
      * VectorDataDSValidation
    * ChangeDetection
      * MultivariateAlterationDetector
    * Classification
      * ComputeImagesStatistics
      * ImageSVMClassifier
      * KMeansClassification
      * SOMClassification (Kohonen Self Organizing Map)
      * TrainSVMImagesClassifier
      * ValidateSVMImagesClassifier
    * DimensionnalityReduction
      * MaximumAutocorrelationFactor
    * Disparitymap
      * FineRegistration
```

```
  * StereoSensorModelToElevationMap
* FeatureExtraction
  * LineSegmentDetection
* Hyperspectral
  * VertexComponentAnalysis
  * HyperspectralUnmixing
* Projections
  * BundleToPerfectSensor
  * ConvertCartoToGeoPoint
  * ConvertSensorToGeoPoint
  * ImageEnvelope
  * ObtainUTMZoneFromGeoPoint
  * OrthoRectification
  * RigidTransformResample
  * Superimpose
* RadiometricIndices
  * RadiometricVegetationIndices
* Radiometry
  * OpticalCalibration
  * SarRadiometricCalibration
* Rasterization
  * Rasterization
* Segmentation
  * ConnectedComponentSegmentation
  * MeanShiftSegmentation
* Utils
  * BandMath
  * ColorMapping
  * CompareImages
  * ConcatenateImages
  * ConcatenateVectorData
  * Convert
  * ExtractROI
  * KmzExport
  * MultiResolutionPyramid
  * OSMDownloader
  * Quicklook
  * ReadImageInfo
  * Rescale
  * Smoothing
  * SplitImage
  * VectorDataExtractROIApplication
  * VectorDataSetField
```

```
        * VectorDataTransform

* System
  * Update internal Ossim to revision 20113
  * Update internal Boost to 1.47.0
  * Update internal OpenJpeg to rev 1111
  * Support for FLTK 1.3
  * Support building ossim as a DLL on windows
  * Support building ossimplugin as a DLL on windows
  * Remove Ossim, OpenThreads and OpenJpeg headers from the install tree
  * Compilation with clang is now possible, still with some constraints :
    * it needs a recent clang version (better use a recent checkout)
    * you may encounter an issue with boost about fenv.hpp : this is a
      boost issue, and is fixed in boost > 1.48

* Monteverdi
  * Support for Pleiades format
    * Support JPEG2000 image loading with multi-resolution choice
    * Quicklook generation based on JPEG2000 format capabilities
    * Support viewing of JPEG2000Images
    * Add module to uncompress an extract of a JPEG2000 image to TIFF
    * Reader module tries to save the quicklook next to the original file
        to improve loading time of JP2 files
  * Fix gaussian histogram stretching mode to avoid warning and black
    image
  * Support Drag'N'Drop of image and vector format into Monteverdi tree
  * Support bundle generation on MacOSX
  * ConnectedComponentSegmentation :
    * Add "Elongation" statistics parameter
    * Support single band image
    * Support extracts of images in sensor model geometry
  * Writer module(s) :
    * Use StreamingImageFileWriter to take advantage of streaming
      improvements
  * Add Monteverdi version number in title bar
  * Reduce KMeans module memory footprint
    * Fix sample list size from an amount of RAM
    * Release temporary filters and variables as soon as possible

* OTB-Applications
  * Removal of command line application migrated to OTB source tree
  * Migration of Viewermanager application to OTB source tree
```

```
* OTB-Wrapping
  * Add otb::Transform

* Bug fixes :
  * OTB-lib
    * 0000501: Add otbcli_XXX.bat and otbgui_XXX.bat for windows
    * 0000478: Exceptions thrown inside applications are not caught
    * 0000479: Can't write int8 image
    * 0000450: In otbViewer, zoom doesn't work well with link mode
    * 0000448: In otbViewer quicklook, navigation coordinate are not
      adapted to multi-res Pleiades images
    * 0000449: In otbViewer, the slide show crashes
    * 0000421: ListSampleGenerator is not random
    * 0000429: Trouble with .geom for Formosat
    * 0000439: Can't run Qt ReadImageInfo
    * 0000428: itkCastImageFilter doesn't work well with streaming
    * 0000416: segfault with non existing input image in the new otb
      applications framework
    * 0000424: Execute button enabling problem
    * 0000393: histogram minimum filter available ?
    * 0000400: how to return objects when function uses a filter ?
    * 0000380: wavelet reconstruction filter problem
    * 0000392: Unable to read Landsat Tiff file. Problem with Tags
      reading ?
    * 0000386: Remove direct use of ossim from Simulation tests
    * 0000401: Error while reading a lum image with several channels
    * 0000381: No platform testing OTB_USE_EXTERNAL_OSSIM
    * 0000441: SWIG/Python interface for applications does not catch
      all exceptions
    * 0000482: The Object Labeling module seems to hold forever when using
      "Save / Quit"
    * 0000471: Multi baseline Test files must begin by 1 and have
      consecutive number
    * 0000485: Hide internal CMake variable
    * 0000419: The new QT applications framework don't work on Ubuntu
      11.04 and Ubuntu 11.11
    * 0000497: Can not save VectorData in cartographic SRS in KML (empty
      file resulting) in applications
    * 0000498: Segmentation fault in Line Segment Detection filter
    * 0000495: StreamingImageFileWriter and link to source filter
    * 0000484: Rename CMake WRAP_* options
    * 0000472: LSD application on sensor image extract produces wrond
      geo-positioning
```

  * 0000491: Build scheduling is buggy with SWIG wrapper
  * 0000418: ld error on exit when using the new application framework with any engines
  * 0000473: Saving TIFF with "degenerated" sizes is highly suboptimal
  * 0000469: Clamp output values to the precision range in new application framework
  * 0000476: baseline file must have extension
  * 0000470: New applications framework input image parameter prevents from accessing to intermediate resolutions
  * 0000423: Internationalisation problem when launching application via Qt
  * 0000453: DEMConvert application becomes ready even if output parameter is empty
  * 0000426: RAM parameter has no effect in the new application framework
  * 0000436: Calling GetParameterXXXImage("in") more than once in DoExecute() breaks streaming
  * 0000442: In otb::WrapperApplication, calling Init() twice results in doubled parameters in examples
  * 0000440: In SWIG/python interface to applications, an exception is thrown when setting parameters unless Init() is called before
  * 0000425: In QT application launcher, some applications are ready to run with missing parameters
  * 0000435: OTB CommandLine wrappers parameters short key
  * 0000434: CommandLine launcher does not report outputs of the MeanShiftApplication
  * 0000431: OTB v. 3.10.0 & Snow Leopard : a bug fixed - Nov. 23, 2011
  * 0000420: command line error reporting is not clear ('-' vs '--')
  * 0000387: [Monteverdi] Unable to display vector data with the viewer
  * 0000390: Lots of warning from itk::Transform when using otb::GenericRSTransform
  * 0000457: Crash of new otbApplications
  * 0000438: KMeans Application crach in Qt Framework

* Monteverdi
  * 0000455: Can't cache a labelimage
  * 0000481: Add a option that allows a compute the histogram on the zoom (or full resolution) area,
  * 0000447: Unable to import non-georeferenced VectorData over a non-georeferenced image without a DEM
  * 0000492: BandMath module closes itself with Help window
  * 0000474: In TileMap Import module, search place by name does not work anymore

```
    * 0000396: Object labeling module crashes
    * 0000408: KMeans clustering crashes after a while
    * 0000383: KMeans module requests the largest possible region
    * 0000477: High memory usage in Monteverdi Viewer module with
      JPEG2000 images
    * 0000480: Viewer crashes playing with histogram method
    * 0000475: Select an Region in the Uncompressed JPEG2000 image module
      QL view constantly increase memory usage
    * 0000464: FLU is not compatible with FLTK 1.3
    * 0000411: Does not support fluid 1.3
    * 0000407: Right click on any list component crashes Monteverdi
    * 0000410: KMZ export module leaves a lot of .jpg.aux.xml files in
      the output directory
    * 0000405: otbSupervisedClassificationApplication does not handle
      class removal properly
    * 0000412: Monteverdi segfaults using contextual menu on module item
    * 0000403: Save dataset (advanced version): Not available for an
      output of bandmath module
    * 0000404: Spectral Viewer keep image locked

  * OTB-wrapping
    * 0000382: Build fails on CentOS 5.5 because of '$self' in java
      wrapper

  * OTB-Packaging
    * 0000500: Make OSGeo4W otb-wrapping-python and otb-wrapping-java
    * 0000502: Package cli and qt launcher in OSGeo4W
    * 0000486: [osgeo4w] Update setup.hint to add osgearth dependency
    * 0000413: Update CentOS installation manual
    * 0000399: Ubuntu packaging for Monteverdi fails (resource files
      are missing)

  * Documentation
    * 0000483: "<" or ">" are interpreted as Â¿ in Cookbook
    * 0000370: Cookbook : make a HTML documentation
    * 0000378: Doxygen not updated


OTB-v.3.10.0 - Changes since version 3.8.0 (2011/06/30)
-------------------------------------------------------
* Monteverdi
  * New Rasterization module
  * New ImageStatistics module
```

```
  * New BayesianFusion module
  * New SAR Polarimetry modules (conversion, analysis)
  * New Vector data to image manual registration module
  * New connected component segmentation and OBIA based on user-defined
    criterions module
  * Removed the Orthorectification since its functionnalities are covered
    by the Reprojection module
  * Specify output map projection by EPSG code in reprojection module
  * Handle multi band complex images
  * Viewer module : Add "save screenshots" feature
  * Viewer module now handles a NoData field, allowing to correctly
    rescale ortho-images
  * DEM fields throughout the modules are now pre-filled with option in
    otb config file if correctly set
  * Add a rectify mode in homologous points extraction module (register
    image without changing resolution)

* Applications with command-line interfaces and GUI
  * Optical calibration
  * Vectorial objects validation based on Dempster Shafer theory framework
    * otbDSFuzzyModelEstimation
    * otbComputePolylineFeatureFromImage
    * otbVectorDataDSValidation
  * Multi-images SVM classification framework
    * EstimateImagesStatistics
    * TrainImagesClassifier
    * ValidateImagesClassifier
    * ImageSVMClassifier
  * Connected Component Segmentation and OBIA based on user-defined
    criterions
  * Object Detection framework (adding the Histogram of Oriented Gradient
    feature)
    * TrainHOGDetector
    * HOGObjectDetector
    * MeanShiftModesDetection
    * TrainDeepSVMDetector
  * Various new utilities :
    * LineSegmentDetection
    * Superimpose
    * RigidTransformResample
    * ConcatenateVectorData
    * VectorDataExtractROIApplication
    * VectorDataTransformFilterApplication
```

```
    * OSMDownloader

* Library
  * Add HistogramOfOrientedGradientCovariantImageFunction
  * Add Framework for LANDSAT Spectral rule based classifier (contribution
    from J. Inglada)
  * Add Multitemporal time point interpolators
    : SavitzkyGolayInterpolationFunctor,
    EnvelopeSavitzkyGolayInterpolationFunctor (contribution from J. Inglada)
  * Add SAR Polarimetry conversions and analysis code :
    * SinclairImageFilter
    * SinclairReciprocalImageFilter
    * SinclairToCircularCovarianceMatrixFunctor
    * SinclairToCoherencyMatrixFunctor
    * SinclairToCovarianceMatrixFunctor
    * SinclairToMuellerMatrixFunctor
    * SinclairToCircularCovarianceMatrixFunctor
    * SinclairToReciprocalCircularCovarianceMatrixFunctor
    * SinclairToReciprocalCoherencyMatrixFunctor
    * SinclairToReciprocalCovarianceMatrixFunctor
    * ReciprocalLinearCovarianceToReciprocalCircularCovarianceFunctor
    * ReciprocalHAlphaFunctor
    * ReciprocalCovarianceToReciprocalCoherencyFunctor
    * ReciprocalCovarianceToCoherencyDegreeFunctor
    * CoherencyToMuellerFunctor
    * MuellerToReciprocalCovarianceFunctor
    * MuellerToPolarisationDegreeAndPowerFunctor
  * Add RationalTransform
  * Add PipelineMemoryPrintEstimator: computes the total memory used by
    a pipeline, and proposes streaming parameters depending on available RAM
  * Add Dempster Shafer framework
    * MassOfBelief
    * JointMassOfBeliefFilter
  * Add a Dempster-Shaffer based vectorial objects validation framework
    * TODO: List classes here
  * AssymmetricFusionOfLineDetectorImageFilter: call SetNumberOfDirections
    on internal filters (contribution from A. Ferro)
  * RADARSAT 1: more product types supported
  * VectorDataToImageFilter: Binary rasterization available, support
    images of arbitrary size
  * Add VectorDataRendering example: showing how to rasterize OSM roads
    onto an image for visualisation
  * LineSegmentDetector & RightAngleDetection: algorithmic improvements
```

```
  * GDALImageIO: multi dataset support (for MODIS HDF4)
  * GDALImageIO: improve performance by avoiding unnecessary memory copies
  * GDALImageIO: TIFF are now saved as TILED
  * GDALImageIO: various improvements to support reading and writing of
    multiband complex data with all types supported by GDAL
  * StreamingImageVirtualFileWriter, StreamingImageFileWriter : new
    streaming strategies, with integrated pipeline memory print estimation
  * Curl:
    * Add in-memory download support to avoid writing small temporary
      files
    * Better handling of the exceptions than can be thrown when using curl
  * Add ConcatenateVectorDataFilter
  * Add OSMDataToVectorDataGenerator : Class implementing the download of
    the OSM file relative to an extent and a parser to generate VectorData
    from OSM Datas
  * Add ImageToOSMVectorDataGenerator : Helper class to compute the extent
    of an image, use OSMDataToVectorDataGenerator for VectorData generation
  * Add VectorDataTransformFilter : Apply an affine transform to a
    VectorData
  * ImageToSURFKeyPointSetFilter : algorithmic improvements
* System
  * Compilation on Windows and MacOS with mapnik
  * Update internal tinyXML to 2.6
  * Add ThirdPartiesUtilities: Refactoring OSSIM and CURL accesses so
    as to minimize dependencies using the Adapter pattern

* Bug fixes :

  * OTB-lib
    * 0000312: Systematic crash when opening images with GDAL (tif, png,
      jpeg, etc)
    * 0000330: Suspicious log and output problem in
      ioImageToKmzAndMapFileProductExport
    * 0000329: At least 2 platforms don't respect the nightly version
      for their dashboard submission
    * 0000298: TestDriver : returns EXIT_SUCCESS when test is not
      registered
    * 0000310: PersistentImageToVectorData process the input twice when
      only one stream is used
    * 0000273: otbHarrisImageFilter applies final smoothing only over
      the 0-th direction; + wrong final scaling applied
    * 0000228: Problems related to the --compare-ascii tool in OTB
      tests protocol
```

```
    * 0000219: HDF dataset not openable with ImageFileReader
    * 0000358: Remove ossim from otbFilterFunctionValuesDigitalGlobeTest
    * 0000320: Design issue: VectorDataIOFactory should not be a
      template class
    * 0000334: Some tutorials do not check argc/argv
    * 0000311: No platform testing OTB_SHOW_ALL_MSG_DEBUG set to ON for
      examples compilation
    * 0000245: Wrong path for GDAL_CONFIG or GDALCONFIG_EXECUTABLE cmake
      variable produce incoherent results in the OTB configuration
    * 0000229: OTB driver in imageFileReader must support different file
      extensions related to the HDF format
    * 0000222: Issues with the TerraSar-X ossim plugin
    * 0000221: Fail to retrieve the pixel spacing from image metadata.
    * 0000282: Unable to open tiff image
    * 0000237: Boost / Fltk conflict
    * 0000327: CMake configuration abort if no curl is available on
      system, even with OTB_USE_CURL is set to OFF
    * 0000276: Trouble with the compare ascii when separations are
      tabulation

  * Monteverdi
    * 0000292: Tilemap import module not working
    * 0000352: Monteverdi crashes on wrong DEM directory
    * 0000270: Open RADARSAT2 products as an SAR image in Monteverdi
    * 0000263: Vectorization module : weird behavior
    * 0000297: Crash when open change detection output image
    * 0000281: Crash opening a RAD image.
    * 0000265: SVM learn module : crash when displaying results
    * 0000254: Homologous point module
    * 0000240: Importing shp file in SVM module in Monterverdi 1.6 always
      results in crash
    * 0000348: Viewer setup : histogram settings disappear
    * 0000349: Labeled image can't be viewed
    * 0000249: otbTrainObjectDetector-cli: malloc(): memory corruption
    * 0000251: Wrong output of the DEM to image generator module when
      working on a ROI of the image in raw geometry
    * 0000226: otbSegmentationApplication: crash when overwriting a
      .shp file
    * 0000223: Wrong positioning of polygons from
      otbSegmentationApplication and open with SVMclassification module
      (monteverdi)
    * 0000242: Mean Shift: different display of results in the module
      and in the Viewer
```

```
  * 0000317: Monteverdi extract ROI module can not perform extraction
    from geographical coordinates on SPOT5 data
  * 0000253: Nodata value in SRTM result in wrong ortho-rectified image
  * 0000315: Monteverdi ROI extraction module broken : can not select
    by drag&drop anymore
  * 0000300: One viewer instance block another instance to display
    another image
  * 0000269: Inoperative fields in the reprojection module
  * 0000255: Image is not visible if scroll or Full window is minimized
    while working with SVM classification
  * 0000267: Vectorization-Rasterization module
  * 0000244: Pansharpening EO-1 image with Monteverdi produces NaN
  * 0000227: Monteverdi crashing while displaying a .tif file
  * 0000350: KMeans module : weird behavior of "Max nb of iterations"
  * 0000248: In feature extraction module, for haralick textures :
    impossible to set min/max for binning
  * 0000341: weird french warning in ms dos command window with
    monteverdi 1.7 exe
  * 0000313: Unable to perform orthofusion of WV2 PAN+XS (4 bands)
  * 0000239: Trouble in pixel descrition in Monteverdi viewer
  * 0000336: Viewer Histogram settings not applied after channel
    order changes
  * 0000304: Advanced save dataset module with scaling on results in
    visible strip in image
  * 0000262: Wrong metadata interpretation
  * 0000302: Can't open two image in the viewer
  * 0000294: Monteverdi doesn't delete files in Caching
  * 0000280: SVM classification and Feature extraction issues
  * 0000247: Style of the new screenshots function in viewer module
    is ugly
  * 0000238: Monteverdi spreads xml temporary files everywhere
  * 0000241: A warning appears each time an image is read
  * 0000271: Default RGB channels are wrong for WV2 images
  * 0000250: Meanshift clustering module: spectral radius limited
  * 0000306: Unable to export otb::Image in KMZ in the Monteverdi module
    "KMZ export"
  * 0000279: Visualisation from vectorisation module does not use
    default channels for wv2 images

* OTB-applications
  * 0000231: otbRasterizationApplication -pr options await for OGC
    WKT strings
  * 0000318: otbOSMDownloader-cli does not work anymore
```

```
    * 0000233: otbRasterizationApplication fail to rasterize SRTM water
      bodies shapefile with default parameters
    * 0000232: Several minor changes in rasterization application
    * 0000338: otbSegmentationApplication : Enable to use real values

  * OTB-Packaging
    * 0000296: gdal 1.8 debian package breaks TIFF support
    * 0000301: Can't upgrade debian package between different OTB versions
    * 0000347: Problem with current ubuntu Natty nightly package of
      Monteverdi
    * 0000290: Make an Experimental submission on the dashboard with natty
    * 0000355: Bad timestamp for nightly built Ubuntu packages
    * 0000288: Nightly packages upload when launchpad is overloaded
    * 0000345: debian package : enable mapnik
    * 0000344: debian package : use system boost
    * 0000326: CentOS packages for Monteverdi and OTB-Applications

  * OTB-Qgis
    * 0000272: problem with installation

OTB-v.3.8.0 - Changes since version 3.6.0 (2010/12/16)
------------------------------------------------------

* Monteverdi
  * New Polarimetric Synthesis module
  * New DEM image extraction / HillShading module: creates an image from
    a DEM tiles directory, with optional hillshading
  * New ColorMapping module: apply a colormap to a mono band image
  * Viewer module: add multi input support, with slideshow or transparency
    mode, add more rendering functions, add splitted/packed layout option
  * Vectorization module: new semi-automatic mode based on segmentation
    results proposals

* Applications
  * Object Detection applications (see also
    http://wiki.orfeo-toolbox.org/index.php/Object_detection)
    * EstimateFeatureStatistics to evaluate descriptors statistics on
      a set of images
    * TrainObjectDetector: generates an SVM model from input images and
      a vector data
    * ObjectDetector: detects points in an image from an SVM model
  * Add automatically generated GUI wrappers for OTB processing chains
    * Add FLTK wrapper
```

```
    * Add a generic Qt based widget class
    * Add a Qt GUI wrapper based on the generic Qt widget
    * Add a Qgis plugin wrapper based on the generic Qt widget

* Library
  * Improved local descriptors tools based on ImageFunction :
    * Rework FlusserImageFunction and HuImageFunction to output
      all moments in one pass (FlusserMomentsImageFunction,
      HuMomentsImageFunction)
    * Rework RealMomentsImagefilter and ComplexMomentImageFilter to
      output a matrix of all moments associated to p, q inferior to a
      given parameter (ComplexMomentsImageFunction, HuMomentsImageFunction)
    * Add image function to compute a vector containing the local mean,
      variance, skewness and kurtosis (RadiometricMomentsImageFunction)
    * Add local histogram image function (LocalHistogramImageFunction)
    * Add image function to compute the local Fourier Mellin coefficients
      (FourierMellinDescriptorsImageFunction)
    * Add a class to adapt any image function return types to
      itk::VariableLengthVector (ImageFunctionAdaptor)
    * Add a class to build composite image functions (MetaImageFunction)
  * New object detection framework (see also
    http://wiki.orfeo-toolbox.org/index.php/Object_detection)
    * Add filter to generate negative samples
      (LabeledSampleLocalizationGenerator)
    * Add filter to evaluate an image function on a set of point and
      generate ListSample (DescriptorsListSampleGenerator)
    * Add filter to balance the sample number of different classes
      in a ListSample by generating new samples from existing
      ones plus noise (ListSampleToBalancedListSampleFilter,
      GaussianAdditiveNoiseSampleListFilter)
    * Add filter to apply a shift/scale to a ListSample
      (ShiftScaleSampleListFilter)
    * Add filter to detect object from an SVM model and an image function
      (ObjectDetectionClassifier)
  * SVMClassifier: add hyperplanes distances as output
  * GDALImageIO: support writing of non-streamable format (JPEG, PNG)
  * Support reading vector images of std::complex
  * BandMathFilter: add physical and image coordinates variables
  * Add a class to generate a kmz file from an image

* System
  * Internal liblas updated to 1.6.0b2 + OTB patches (root CMakeList.txt)
  * Internal libsvm updated to 3.0 + OTB patches (additionnal kernels)
```

```
  * Internal ITK: removed compilation of medical image formats library
    and associated ImageIO
  * Internal ITK: removed dependency on libtiff, libjpeg, libpng and zlib,
    now handled by gdal
  * Support for gcc-4.5
  * Remove dxflib from Utilities for licensing issues

* Bug fix:
  * Monteverdi
    * 0000216: Monteverdi viewer unable to display multi band images
    * 0000193: Crash in vectorization module when the after the activation
      of the semi-automatic mode
    * 0000195: unable to perform TSX calibration with the sar calibration
      module in monteverdi 1.4
    * 0000207: Vectorization module shift coordinates
    * 0000202: Error message "otbSVMModel.txx:310 eps <= 0" in the SVM
      classification module
    * 0000194: error message opening dataset in monteverdi (development
      version)
    * 0000200: Monteverdi -in option does not open viewer anymore

  * OTB-applications
    * 0000213: Problem in denomination of otb process chain wrapped as
      qgis plugin
    * 0000201: otbFastOrthoRectif switched back to double precision again

  * OTB-lib
    * 0000192: Crappy support of gdal: GDALImageIO


OTB-v.3.6.0 - Changes since version 3.4.0 (2010/10/07)
------------------------------------------------------

* Monteverdi
  * New Vectorization module: creates vector data (polygons, lines and
    points) from image
  * New BandMath module: mathematical operation on image bands
  * New SpectralViewer module: designed to display hyperspectral
    images. also computes spectral angle
  * New ObjectLabeling module: object based image analysis module,
    with SVM classification based on object features

* Applications
```

```
  * otbFastOrthoRectif: fast orthorectification based on grid subsampling
  * otbActiveLearning: architecture to enable active learning application
    (put your own algorithms in the middle)
  * otbCompareImages: image comparison
  * otbFineRegistration: produces disparity maps between 2 images
  * Old GUI applications removed (now in Monteverdi): OrthoRectif,
    OrthoFusion, Classif, ChangeDetection, RadiometricCorrections

* Library
  * Some classes are marked as deprecated and are available for one
    release. A migration guide to help the transition is available at
    http://wiki.orfeo-toolbox.org/index.php/Migration_guide
  * Add filter to perform arbitrary mathematical operation on image bands
    (BandMathImageFilter)
  * Add class to parse mathematical expression (Parser)
  * Add interpolation function (BCOInterpolateImageFunction)
  * Add filter to compute the intensity of a complex image
    (ComplexToIntensityImageFilter)
  * Add filter to compare two big images (StreamingCompareImageFilter)
  * Add filters to compute extrema of big images
    (StreamingMinMaxImageFilter and StreamingMinMaxVectorImageFilter)
  * Add filter to perform fine registration between images
    (FineRegistrationImageFilter)
  * Add filter for higher order texture computation
    (ScalarImageToHigherOrderTexturesFilter and
    MaskedScalarImageToGreyLevelRunLengthMatrixGenerator)
  * Removal of the old textures:
    http://wiki.orfeo-toolbox.org/index.php/Textures
  * Add support for Worldview2 data
  * Add margin sampler for SVM (SVMMarginSampler)
  * Add generic resample filter that reproject in any arbitrary
    projection: cartographic, sensor model (GenericRSResampleImageFilter)
  * Add class to produce a RPC model from a physical model
    (PhysicalToRPCSensorModelImageFilter)
  * Add classes related to SAR calibration (SarParametricMapFunction,
    SarRadiometricCalibrationFunction, SarRadiometricCalibrationFunctor,
    SarRadiometricCalibrationToImageFilter)
  * Add an action handler for the visualization enabling dragging
    (DragFullWindowActionHandler)

* System
  * Internal ITK updated to 3.20.0 + OTB Patches
  * Internal OSSIM and ossim plugins updated to svn revision 18162 +
```

```
    OTB patches (almost none left)
  * Enable the use of an external build of libLAS
  * Support compilation on MSVC 2010 and Windows Seven
  * Better handling of FLTK configuration
  * Support compilation of Monteverdi on linux 32 bits systems with
    official FLTK package
  * Lots of coverage improvements

OTB-v.3.4.0 - Changes since version 3.2.0 (2010/06/30)
------------------------------------------------------

* Applications
  * New utility otbConvertSensorToGeoPoint to convert from sensor
    coordinates to lon/lat
  * otbExtractROI can change its output type
  * New utility otbSplitImage to separate a multispectral image into
    N images
  * otbConcatenateImage can change its output type
  * otbConvert can now use a log transfer function when rescaling
    the image

* Library
  * Add HillShadingFilter to produce hill shade image from DEM
    (HillShadingFilter)
  * Add point set density function (gaussian, epanechnikov)
  * Add filter to extract a subset from a point set (PointSetExtractROI)
  * Add filter to apply a transform to a point set
    (TransformPointSetFilter)
  * Add filter to generate a random point set (RandomPointSetSource)
  * Add class to compute confusion matrix (ConfusionMatrixCalculator)
  * Add class to generate a list of samples from a vector data
    (ListSampleGenerator)
  * Add a class to compute the ground spacing (GroundSpacingImageFunction)
  * Add a class to read 6S spectral sensitivity files
    (SpectralSensitivityReader)
  * Fix radiometry correction for SPOT5
  * Fix compilation on windows using osgeo4w dependencies
  * Lots of bug fixes

* System
  * Internal ITK updated to 3.18.0 + OTB Patches
  * Internal OSSIM updated to svn revision 16861 + OTB patches
  * Internal OSSIM SAR plugins updated to svn revision 17643 + OTB patches
```

```
  * Internal libkml updated to 1.2.0
  * Internal siftfast updated to 1.2
  * Internal boost updated to 1.42


OTB-v.3.2.0 - Changes since version 3.0.0 (2010/01/15)
------------------------------------------------------

* Applications
  * Monteverdi, a new all-in one user-friendly graphical tool
      for remote sensing data processing released as a separate package
      (see README file). Windows binary package of Monteverdi is available
      and was installed on various operating system including
      Windows 2000/XP/Vista/Seven.

* Library
    The library includes these additions
  * Support for TerraSarX, Quickbird and Spot5 calibration metadata
  * Simplification of the interface to access image metadata
  * Support for Aeronet files
  * Various filters for Object Based Image Analysis based on
    LabelObjectMaps
  * Support for RPC sensor model estimation from a set of Ground Control
    Points
  * Support for affine transform least-square estimation from a set of
    tie points
  * Support for SVM cross-validation and parameters optimization
  * Box and Whiskey filter to detect outliers on VectorImage
  * Add several Euclidian distance classes
  * Exhaustive exponential optimizer for learning
  * Enhanced SOM algorithm taking into account invalid missing values
  * Wavelet transform
  * Filters for GIS database interaction (postgis database)
  * ImageFileWriter now supports streaming natively
  * Use of a configuration file to change some parameters without
    recompiling
  * Lots of bug fixes

* System
  * Internal ITK updated to 3.16.0 + OTB Patches
  * Internal OSSIM updated to svn revision 15872 + OTB patches
  * Home brewed metadata SAR reader were moved to ossimplugins
  * Experimental support for internationalization
```

```
  * Facilitate installation on Mac OSX platform (OTB is now able
    to compile on Mac OSX by using external libraries like GDAL downloaded
    from Macports)



OTB-v.3.0.0 - Changes since version 2.8.0 (2009/05/11)
------------------------------------------------------

* Applications
  - Urban area extraction (PlÃ©aides, QB, Ikonos, SPOT5). For more
    details,
    see the README file
  - Image to Data Base registration (PlÃ©iades, QB). For more details, see
    the README file
  - Feature Extraction: add new textures, new radiometric indexes and
    add MeanShift capabilities


* Library
    The library includes these additions
  - Cloud detection for QB/PlÃ©iades images
  - Alignment and right angle detection (Burns, Grompone)
  - Radiometric indices (vegetation, water, soil)
  - Optimized texture computations including Haralick, SFS, Pantex,
    Edge density
  - SIFT density image function and filter
  - Object-based segmentation and filtering
  - LSD line segment detector and right angle detector
  - PCA computation
  - Automated loading of radiometric correction parameters (SPOT, Ikonos)
  - Attribute support for shapefile (reading only)
  - Optimization of vector data
  - Visualisation refactoring: for more details,
     see http://wiki.orfeo-toolbox.org/index.php/Visualisation_Refactoring

* System
  - Updated OSSIM library
  - Updated ITK library (3.12.0)
  - Miscellaneous bug fixes (support for gdal 1.6)
  - Fixed some problems under Visual and Cygwin platforms.

* Distribution
```

```
  - Distribution of Windows binaries packages installation for
    OTB-Application (OTB-Applications-3.0.0-win32.exe)
  - Distribution of Windows binaries packages for GDAL library 1.6.0 for
    MSVC V71 and MSVC V80 compiler (http://www.orfeo-toolbox.org/packages)


OTB-v.2.8.0 - Changes since version 2.6.0 (2009/01/15)
------------------------------------------------------

* System
- ITK version updated to 3.10.1
- liblas library added
- ossim gdal plugin added
- change in OpenGL access for viewer
- Edison code from mean shift

* Library
- Support for Lidat data
- SIFT and SURF implementation
- Mean Shift algorithm
- Conversion of vector data projection (kml, shapefiles)

* Applications
- Object counting
- Fine Registration
- Road Extraction



OTB-v.2.6.0 - Changes since version 2.4.0 (2008/10/31)
------------------------------------------------------

* System
- GCC 4.3 compatibility
- ITK version updated to 3.8
- FLTK version updated to 1.1.9
- OpenThreads library added
- Expat library added

* Library
- SAR Polarimetry synthesis classes
- Kullback Leibler supervised change detection
- KML support
```

```
- Gabor filters implementation
- Optimized convolution using FFT
- CNES RAD format support
- NCC and MI registration filters for diparity map estimation
- Support for MegaWave image format (contributed by Eric Bughin)

* Applications
- Object segmentation application
- Feature extraction application
- Land Cover Map application
- SAR polarimetric synthesis application
- 3D & stereo anaglyh viewer application
- Command line conversion from/to all image formats supported
  by OTB


OTB-v.2.4.0 - Changes since version 2.2.0 (2008/07/24)
------------------------------------------------------

- Added OTB_DISABLE_CXX_EXAMPLES_TESTING : allows to generate or
  not only examples testing
- Added OTB_USE_JPEG2000 : experimental support for jpeg2000
  files.

*Common:

  Extraction ROI Classes :
- Lifting of the otbExtractionBase classe
- Correction of the SetExtractionRegion method

*BasicFilters:

- Added pixel size matching in otbSpectralAngleDistanceImageFilter
- Modification of otb::ConvolutionImageFilter class to allow the
  use of non-normalized convolution filters

*Platforms:

- Fixed compilation problems using external FLTK version < 1.1.9
  under fedora unix distribution.
- Mac OS X 10.5 supported

*Applications:
```

```
- Added an supervised image classification application
  (otbSupervisedClassification)
- Added an orthorectifcation application (otbOrthoRectifAppli)
- Added an orthofusion application (otbOrthoFusionAppli)

*Markov:
  Added full Markov framework for segmentation, restauration
  and filtering
  Added related classes:
- otb::MarkovRandomFieldFilter
- otb::MRFEnergyEdgeFidelity
- otb::MRFEnergyGaussianClassification
- otb::MRFEnergyGaussian
- otb::MRFEnergy
- otb::MRFEnergyPotts
- otb::MRFOptimizer
- otb::MRFOptimizerICM
- otb::MRFOptimizerMetropolis
- otb::MRFSampler
- otb::MRFSamplerMAP
- otb::MRFSamplerRandom
- otb::MRFSamplerRandomMAP
  Added related examples:
- MarkovClassification1Example
- MarkovClassification2Example
- MarkovRegularizationExample
- MarkovRestaurationExample

*Projections
  Added Lambert 93 cartographic projection with
  otb::Lambert93Projection class

* Utilities:

  - Corrections on new SAR models integrated to OSSIM during release 2.2.0

OTB-v.2.2.0 - Changes since version 2.0.0 (2008/05/29)
------------------------------------------------------


*BasicFilters:
```

```
  Added classes for data importation:
- otb::ImportImageFilter
- otb::ImportVectorImageFilter
  Added classes for image interpolation:
- otb::WindowedSincInterpolateImageBlackmanFunction
- otb::WindowedSincInterpolateImageCosineFunction
- otb::WindowedSincInterpolateImageGaussianFunction
- otb::WindowedSincInterpolateImageHammingFunction
- otb::WindowedSincInterpolateImageLanczosFunction
- otb::WindowedSincInterpolateImageWelchFunction
- otb::ProlateInterpolateImageFunction
  Added class for resampling
- otb::RationalQuotientResampleImageFilter
  Added classes for labelization
- otb::LabelizeImageFilterBase
- otb::LabelizeConfidenceConnectedImageFilter
- otb::LabelizeConnectedThresholdImageFilter
- otb::LabelizeNeighborhoodConnectedImageFilter

*Radiometry:

- Bug fixed on otb::DEMCaracteristicExtractor

*Visu

- Added histogram windows in otb::ImageViewer main class.
- Added polygon drawing support in otb::ImageViewer main class

*IO:

- Fixed bug in GDALImageIO to handle complex images
  Added classes for vector data use:
- otb::VectorDataFileReader
- otb::VectorDataFileWriter
- otb::VectorDataIOFactory
- otb::VectorDataSource

*Common:

  Added classes to handle vector data:
- otb::Polygon
- otb::VectorData
- otb::DataNode
```

```
  Added classes to watch filter progression (ASCII mode):
- otb::StandardFilterWatcher
- otb::FilterWatcherBase

*Learning:

- Creation otb::SVMKernels containing a list a useful kernel
  for SVM
- Correction in Kohonen map classes
- Added convenience methods in SVMModel class

  Added classification filters (streamed and threaded):
- otb::SVMImageClassificationFilter
- otb::SOMImageClassificationFilter
- otb::KMeansImageClassificationFilter

*FeatureExtraction:

  Added implementation of Scalar Invariant Feature Transform
- otb::ImageToSIFTKeyPointSetFilter

*MultiScale:

  Added mono and multi-scale convex/concave image classification
         based on geodesic morphology characteristics.
- otb::ConvexOrConcaveClassificationFilter
- otb::GeodesicMorphologyDecompositionImageFilter
- otb::GeodesicMorphologyIterativeDecompositionImageFilter
- otb::GeodesicMorphologyLevelingFilter
- otb::ImageToProfileFilter
- otb::MorphologicalClosingProfileFilter
- otb::MorphologicalOpeningProfileFilter
- otb::MultiScaleConvexOrConcaveClassificationFilter
- otb::ProfileDerivativeToMultiScaleCharacteristicsFilter
- otb::ProfileToProfileDerivativeFilter

*Utilities:

- Updated the internal version of ITK to 3.6.0
- Corrections on OSSIM integration
- SVM library: creation of otb::ComposedKernelFunctor
  allowing composed kernels
```

```
- Added SAR models in OSSIM library:
  . Radarsat 1 (SGX and SGF)
  . Envisat ASAR - SLC (IMS, APS) and PRI (IMP, APP)
  . ERS - SLC and PRI
  . Terrasar X - SLC and PRI
  . Cosmo-Skymed - SLC and PRI
  . Radarsat 2 - SLC and PRI
- Bug fixed in CMake configuration
- Added SIFT implementation in InsigthJournal

*Applications:
- Various Bug fix
- otbConvertGeoToCartoPoint and otbConvertCartoToGeoPoint map
  precision enhancement
- Added of histogram manipulation functionalities in
  otbImageViewer
- Added of shape file functionalities and large image support in
  ICD application
- Added otbConcatenateImages application to concatenate multiple
  image in the spectral domain
- Added an unsupervised image classification application based
  on the KMeans algorithm (otbKMeansClassification)
- Added an unsupervised image classification application based
  on the SOM algorithm (otbSOMClassification)
- Added an unsupervised image classification application based
  on the SVM algorithm (otbSVMClassification)
- Added an application to create a contiguous unsigned short
  labeled image from a colored labeled image
  (otbUnsignedShortRelabeling)
- Added an application to create a colored labeled image from an
  unsigned short labeled image (otbRgbRelabeling)

*Examples:
- Added SIFT example (otb)
- Added SIFT example (ij)
- Added LabelizeNeighborhoodConnected example
- Added RationQuotientResample example

*Platforms:

- Fixed some problems under Visual, Cygwin and MinGW platforms.
```

```
OTB-v.2.0.0 - Changes since version 1.6.0 (2007/12/14)
------------------------------------------------------


*Projections

- Bug correction in otb::OrthoRectificationFilter

*Fusion

- Added simple Pansharpening algorithm
- Fixed streaming bug on BayesianFusion filter

*Radiometry:

  Added classes for atmospheric correction using the 6S Radiative
  Transfer Code:
- Luminance estimation otb::ImageToLuminanceImageFilter
- Reflectance estimation TOA:
  otb::LuminanceToReflectanceImageFilter
- Added Composite transform filter:
  otb::ImageToReflectanceImageFilter,
    equivalent to the pipeline process ImageToLuminanceImageFilter
    and LuminanceToReflectanceImageFilter filters
- Reflectance estimation TOC:
  otb::ReflectanceToSurfaceReflectanceImageFilter
- 6S effect correction:
  otb::SurfaceAdjacencyEffect6SCorrectionSchemeFilter
- DEM slope and shading estimations:
  otb::DEMCaracteriticsExtractor

*Common:

- Added otb::UnaryFunctorNeighborhoodVectorImageFilter
- Fixed bug on otb::ExtractROIBase class

*IO:

- Bug fixed on otb::VectorImage class

*BasicFilters:

- Bug correction in otb::StreamingStatisticsVectorImageFilter,
```

```
  otb::StreamingStatisticsImageFilter,StreamingMatrixTransposeMatrixImageFilter
- Added PrintableImageFilter
- Fixed bugs on otb::FrostImageFilter and otb::LeeImageFilter

*Utilities:

- Fixed memory allocation bug on svm.cxx file
- 4 files from ITK 3.4.0 have been replaced by the cvs version
  to allow
  correct use of the itkDivideImageFilter.h with VectorImage. These
  files
  are:
      Common/itkNumericTraitsVariableLengthVectorPixel.h
      Common/itkNumericTraitsVariableLengthVectorPixel.cxx
      Common/itkConceptChecking.h
      BasicFilters/itkDivideImageFilter.h

*Examples

- Tutorials: Added OrthoFusion example
- Radiometry: Added AtmosphericCorrectionSequencement example

*Applications:

- Rename Pireo application to otbPireo
- Added transform coordinate point applications:
  otbConvertCartoToGeo
  otbConvertGeoToCarto
- Pireo corrections in CMakeLists.txt (GUI dir source code) and
  source code (suppress of call VnlModifiedOptimizer class)

*Platforms:

- Fixed some problems under Visual and MinGW platforms.



OTB-v.1.6.0 - Changes since version 1.4.0 (2007/10/25)
------------------------------------------------------

*BasicFilters:

- Added StreamingVectorStatisticsImageFilter to compute
```

```
  the second order stastics on a large vector image.

- Added the MatrixTransposeMatrixImageFilter to compute
  the product of the matrix of vector pixels from image 1
  in rowwith the the matrix of vector pixels from image 2
  columns for large vector image.

        - Added the otb::VectorImageTo3DScalarImageFilter which transforms
          a vector image into a 3D scalar image where each band is
          represented
          in a layer of the 3rd dimension.

        - Added the otb::ImageListToVectorImageFilter and
          otb::VectorImageToImageListFilter to convert a vector image
          from/to an image list.

        - Added the otb::ImageListToImageListApplyFilter which applies
          a given
          scalar image filter to a list of images

        - Added the otb::PerBandImageFilter, which applies a given
          scalar filter
          to each band of a VectorImage. This is not the optimal way for most
          processings but it allows the use of almost every scalar filter on
          vector images.

        - Added the otb::StreamingResampleImageFilter, which is a
          streaming capable
          version of the itk::ResampleImageFilter.

*ChangeDetection:

- Added the otb::KullbackLeiblerDistanceImageFilter to compute the
  Kullback-Leibler distance between two images.

- Added the otb::KullbackLeiblerProfileImageFilter to perform a
  multi-scale change detection using the Kullback-Leibler distance.


*Common:

- Added an otb::Polygon, which represents a closed polyline
  on which
```

```
  intersection or point interiority can be tested.

*IO:

- Added an otb::DEMHandler to fetch the elevation value in
  SRTMor DTED
    directories.

- Added an otb::DEMToImageGenerator to generate an elevation map.

- Added a new tiling streaming mode.

- Added the otb::ImageGeometryHandler, which allows to handle
  seamlessly
  the image geometry information.

- Fixed a bug in the otb::MSTARImageIO.

*Learning:

- Added methods to access the alpha values, the number of
  support vectors,
  the support vectors themselves, the distance to the hyperplanes.

- Added the otb::SEMClassifier, implementing the Stochastic
  Expectation
  Maximization algorithm to perform an estimation of a mixture
  model.

*MultiScale:

- Various name changes and bugfixes in the morphological pyramid
  segmentation classes.

*Radiometry:

- The 6S Transfer Radiative Code compiles within OTB.
- Added the Radiometry directory, containing everything that
  has to do
  with image radiometry.
- Added the NDVI and ARVI (3 input bands) vegetation index
  filters.
```

```
*Projections:

- Added the Projections directory, containing everything that
  has to do
  with image projections.

- Added an otb::DEMHandler to fetch the elevation value in
  SRTM/DTED
    directories.

- Added an otb::DEMToImageGenerator to generate an elevation map.

- Added an otb::OrthoRectificationFilter to perform
  orthorectification of
  geo-referenced images.

- Added the forward and inverse sensor model projection.

- Added several map projection transforms (Eckert4,
  LambertConformalConic,
  TransMercator, Mollweid, Sinusoidal, UTM)

*Fusion:

- Added the Fusion directory, containing everything that has to do
  with image fusion.

- Added the otb::BayesianFusionImageFilter, a pan-sharpening
  filter which
  algoritm has been kindly contributed by Julien Radoux.


*Documentation:

- Added various documented examples in the SoftwareGuide for
  the new classes.

- Added a Tutorial section in the SoftwareGuide.

*Utilities:

- Added the 6S library which will soon play a role in the
  radiometry module.
```

```
- Updated the internal version of ITK to 3.4.0.

*Platforms:

- Fixed the random segfault of otbInteractiveChangeDetectionAppli
  under Visual 8.0.

*Applications:

- Added the otbImageViewerManager application which allows to
  open multiple images,
  configure viewers and link displays.

- Added the otbRoadExtraction which demonstrates the road
  extraction algorithm
  implemented in the FeatureExtraction module.

- Added the otbOrthoRectifAppli application which allows to
  ortho rectify images in
  command line using the brand new Projections module of the Orfeo
  ToolBox. Old rigid
  orthoo rectification application has been moved to
  otbPseudoOrthoRectif.

- Added an option in CMakeLists.txt to use VTK or not (enable
  or disable the
  following application).

- Added the Pireo registration application (VTK needed).


OTB-v.1.4.1 - Changes since version 1.4.0
-----------------------------------------------------------

*Platforms:
- Minor corrections of main ./CMakeLists.txt to support users
  applications using OTB
    install directory when using internal ITK.

OTB-v.1.4.0 - Changes since version 1.2.1
-----------------------------------------------------------
```

*IO:

- Added the LineSpatialObject class.

- Added the ArcSpatialObject class.

- Added a DXF file reader to read spatial objects from DXF files.

*Common:

- Added a PolylineParametricPathWithValue class, to store a
  scalar value along with
    a polyline.

- DrawPathFilter and DrawPathListFilter can now use the internal
  scalar values of the path(if present) as a value to draw the path.

- Improved performances of the DrawPathFilter and
  DrawPathListFilter.

- Added the base class
  otbBinaryFunctorNeighborhoodVectorImageFilter (see
  ChangeDetection)

*BasicFilters:

- Added the ImportGeoInformationImageFilter providing a workaround
  for metadata handling in pipeline execution.

- Added a VectorRescaleIntensityImageFilter, which rescales
  a vector
  image on a per-band basis, clamping a user-defined percent of the
  pixels lowest and highest values.

- Added a filter to compute spectral angle distance image with
  respect to a reference pixel.

*FeatureExtraction:

- Added a set of image and path filters to perform road
  extraction.

- Added a composite filter to perform road extraction.

```
*ChangeDetection:

    - Added the Kullback-Leibler distance change detector with optimized
      algorithm.

- Added a Kullback-Leibler multi-scale change profile image filter
  with optimized algorithm.

*DisparityMap:

- Added the DisparityMapEstimationMethod, performing local
  disparity
  estimation with respect to a given transform using the ITK
  registration framework.

- Added several methods for deformation field estimation from
  the estimated disparity map (represented as a pointset with
  associated point data).

*Documentation:

- Corrected several warning and French comments in doxygen.

*Utilities:

- Split of the OSSIM lib to support compilation on the mingw
  platform.

- DXFlib integration.

- InsightJournal code integration :
  ScatteredDataPointSetImageFilter.

*Platforms:

- Corrected runtime errors of the interactive change detection
  application under cygwin.

- Workaround for ImageViewer on very specific mandrake version.


OTB-v.1.2.1 - Changes since version 1.2.0
```

```
-----------------------------------------------------

*IO:
- Improved support of geographic meta data handling in pipeline
  execution.

*BasicFilters:
- Added a cast filter otb::ImageToVectorImageCastFilter to convert
    otb::Image (templated with scalar pixel types) to
    mono-channel otb::VectorImage.

*FeatureExtraction:
    - Added a contour extraction filter otb::ImageToEdgePathFilter.

*Visualization:
    - Viewer accepts now otb::Image (templated with scalar pixel types)
    as well as otb::VectorImage.
    - Added FlRun() method to the Viewer, which execute Show() method from
    the Viewer followed by the Fl::run() method from FLTK.

*Platforms:
- Minor correction of otb::ObjectList and otb::List in order
  to support
        visual 7.0 compiler.

*Experimental:
    - Support for python binding compilation including itk binding
    templated with OTB images, OTB IO and OTB Image viewer.
    - OSSIM has been integrated in the OTB Utilities directory to
    prepare its future use in new geometric features.


OTB-v.1.2.0 - Changes since version 1.0.2
-----------------------------------------------------

*Platforms:
- OTB can now been compiled on several new platforms :
  - SunOS 5.8 (32bits and 64bits).

- Improved robustness of
  - the Microsoft Visual Studio .NET 2003 (7.1), .NET 2005 (8.0)
  - the Cygwin and MinGW installation.
```

```
*Common:

- Various bug fixes and warning corrections.

- Added support for ObjectList (ie SmartPointers) and thus
    support for ImageList.

- Added base classes for image to image list filters, image
    list to image filters, image list to image list filters.

- Precision for internal calculus has been tuned to double in
    every filter.

*Multiscale:

- Added filters for multiscale analysis and synthesis based on
    the morphological pyramid algorithm.

- Added automated region-growing multiscale segmentation
    algorithm based on the morphological pyramid analysis.

*Spatial Reasoning:

- Added support for graph representation of RCC8 spatial
     reasoning relationships.

- Added filters for atomic RCC8 computation based on two
    segmented regions.

- Added filter for multiscale segmentation to RCC8 graph
    calculation with optimisations.

*IO:

- Added full support (reading and writing) of the HFA image
    format (ERDAS img files).

 - Bug fixes on metada writing (now works for tif and HFA
     formats, limited support envi header file formats due to
     Gdal limitations).

- Bug fixes on memory management in the Reader.
```

```
- Bug fixes related to the IO framework on MS Windows platforms.

*Learning:

- Added filters for learning, classification and activation
    map of data sets using Kohonen's self organizing maps.

*Visualization:

- Re-factoring of the base classes for visualization.

- Re-factoring of the viewer object (and viewer apps). The
    viewer can now be used to visualised large remote-sensing
    images (Quickbird, Spot5) with limited memory footprint.


*Applications:

- Minor changes needed for the portability of OTB-Applications.

- Added a viewer application in OTB-Applications.

- Added a interactive change detection application in
  OTB-Applications.


OTB-v.1.0.2 - Changes since version 1.0.1
------------------------------------------------------

- OTB can now been compiled on several new platforms :
       - Microsoft Visual Studio .NET 2005 (8.0).
       - Cygwin.
       - MinGW on Windows platform.

- LUM and BSQ formats have been added.


Note : On MS Windows platforms, if you have any problem related
         to using the OTB's internal version of ITK, you could try to use
         an external version of ITK (use ITK 2.6 or later) by setting
         OTB_USE_EXTERNAL_ITK to ON and ITK_DIR to the directory where
         your ITK built resides.
```

```
OTB-v.1.0.1 - Changes since version 1.0.0
---------------------------------------------------------

- Building the visualization functionnalities is now an option
    (OTB_USE_VISU variable within CMake). This allows you to build OTB
    without Fltk and Open GL.

- Improved robustness of the Microsoft Visual Studio .NET 2003 (7.1)
installation.

- Minor changes needed for the portability of OTB-Applications.

- Bugfixes related to the IO framework on MS Windows platforms.
```

CHAPTER

THIRTYTHREE

WRAPPINGS TO OTHER LANGUAGES

33.1 OTB-Wrapping: bindings to Java language

OTB-Wrapping was a project designed to allow classes from OTB to be wrapped for use with languages like Python, and Java and Tcl. However, OTB-Wrapping is not supported anymore since OTB 4.0.

CHAPTER

THIRTYFOUR

CONTRIBUTORS

The ORFEO Toolbox is a project conducted by CNES and developed in cooperation with CS (Communication & Systèmes), `http://www.c-s.fr`.

This Software Guide is based on the ITK Software Guide: the build process for the documentation, many examples and even the LaTeX sources were taken from ITK. We are very grateful to the ITK developers and contributors and especially to Luis Ibáñez.

The OTB specifics were implemented and documented by the OTB Development Team with some help from several contributors. Without these people[1], OTB will not be where it is today:

Tishampati Dhar, Guillaume Pasero (CNES Intern, then CS), Jordi Inglada (CNES), Aik Song Chia (CRISP), Christophe Lay, Yannick Reynard, Mathieu Deltorre (CS), Julien Michel (CS then CNES), Emmanuel Christophe (CNES, then CRISP, then Google), Angelos Tzotsos, Michael Seymour (EADS), Amit Kulkarni, Aurélien Bricier (CS), Vincent Schut (Sarvision), Etienne Bougoin (CS), Mickael Savinaud (CS), Otmane Lahlou (CS), Patrick Imbo (CS), Adamo Ferro, Sébastien Harasse (CS), Alexis Huck (Magellium), Luc Hermitte (CS), Charles Peyrega (CS), Jens Ziehn (CNES Intern), Thomas Feuvrier (CS), Jonathan Guinet (CS), Stéphane Albert (CS), Conrad Bielski (JRC), Jan Wegner, Mohammed Rashad (CNES Intern), Julien Osman, Rik Bellens, Guillaume Borrut (CS), Sébastien Dinot (CS), Massimo Di Stefano, Stephane May (CNES), Gwendoline Blanchet (CNES), Antonio Valentino, Cyrille Valladeau (CS), Manuel Grizonnet (CNES), Edouard Barthelet (Telecom Bretagne and Thales Communications), David Youssefi (CNES Intern, then CS), Jean-Guilhem Cailton (Arkémie), David Dubois, Eric Bughin (CMLA), Vincent Poulain (CNES), Julien Malik (CS), Romain Garrigues (CS), Grégoire Mercier (Telecom Bretagne), Caroline Ruffel (CS), Julien Radoux (UCL)

Contributions from users are expected and encouraged for the coming versions of the ORFEO ToolBox.

[1] this list has been generated at random without any hierarchy or amount of contribution consideration

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