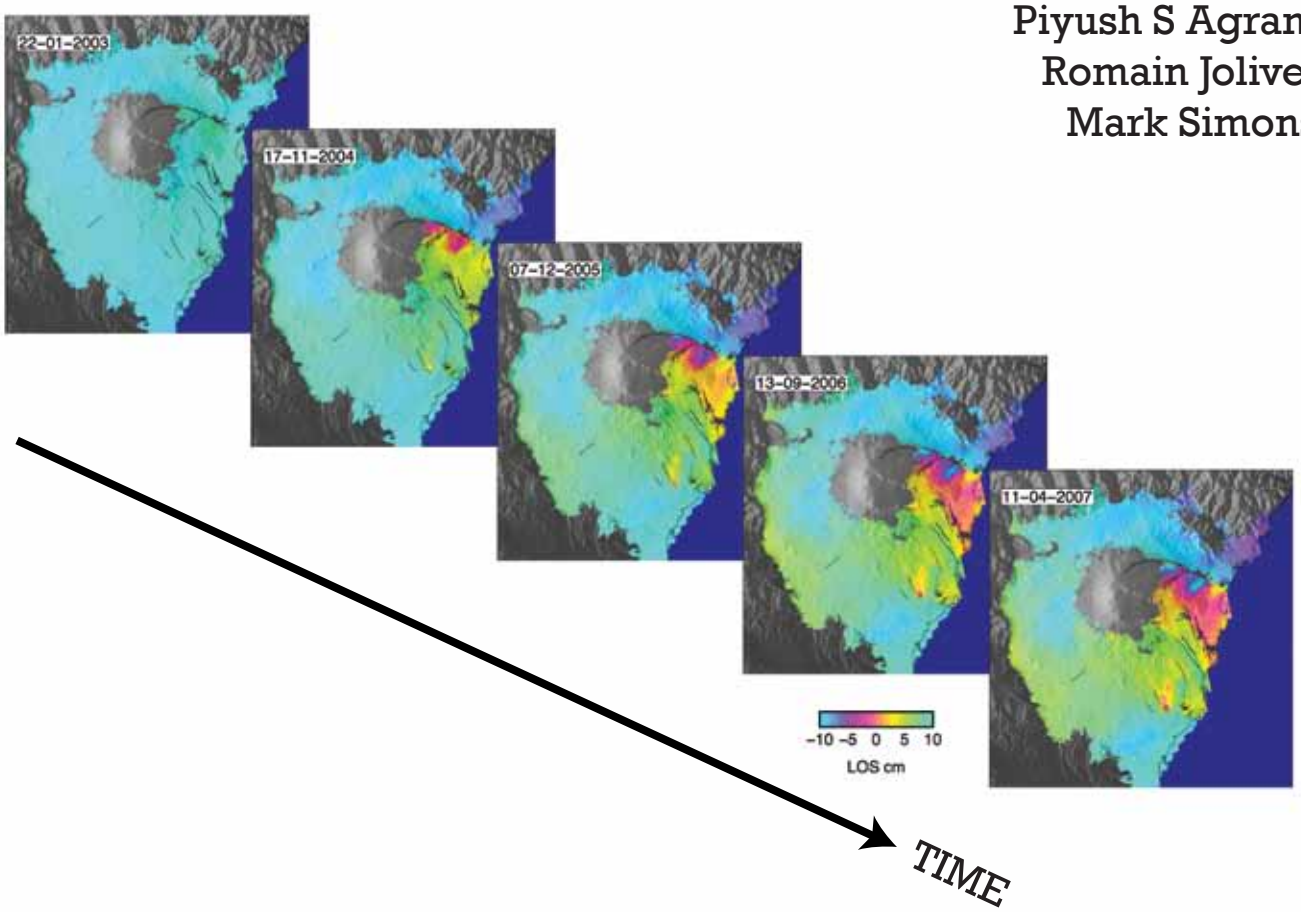
GIAnT

The Generic InSAR Analysis Toolbox

User Manual



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[1] Velocity estimates

Preface

0.1 About This Document

This document describes GIAnT. It is organized following the steps most users will follow for their interferometric SAR time series processing. We begin with a description of how to install the software, with extensive details for Linux and OS-X users. We have not tested this software on a Windows platform. We then describe, step by step, the different techniques implemented in GIAnT.

0.2 Who Will Use This Documentation

This documentation is designed for both scientists who are content to use pre-packaged tools for analysing their synthetic aperture radar (SAR) interferogram stack and for experienced interferometric SAR (InSAR) time-series algorithm developers. The latter are likely to want to study the source code, compare the performance of numerous algorithms and even incorporate additional processing approaches into GIAnT. Users who want to modify the source will need to have familiarity with scripting, software installation, and programming, but are not necessarily professional programmers. We hope that any user-improvements will be shared with the developers so that all users can benefit from them.

0.3 Citation

We make this source code available at no cost in hopes that the software will enhance your research. Commercial use of any part of this software is not allowed without express permission from the authors.

A number of individuals have contributed significant time and effort towards the development of this software. Please recognize these individuals by citing the relevant peer-reviewed papers and making relevant acknowledgements in talks and publications.

[[[Include citations when ready.]]]

0.4 Acknowledgements and Credits

The authors of this software were supported by NASA solid earth and natural hazards program (NNX09AD25G), the Keck Institute for Space Studies (KISS) and the Caltech Tectonics Observatory (CTO). The Authors thank the Gordon and Betty Moore foundation for financial support of the CTO.

The authors thank all those people who contributed in helping to develop this program and those who volunteered to be guinea pigs, among them B. Riel, G. Peltzer, C. Lasserre and M.-P. Doin.

The data used to generate the front page graphics were provided by Marie-Pierre Doin, ISTerre, France. The data processing from the raw SAR data to the interferograms is described in Doin et al. [2011]. We produced the time series using GIAnT. The snapshots are created using the Generic Mapping Tool [Wessel and Smith, 1995].

0.5 Request for feedback

Your suggestions and corrections are essential to improve this software suite and the documentation. Please report any errors, inaccuracies or typos to the GIAnT development team at earthdef@gps.caltech.edu.

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Chapter 1

Introduction

1.1 Overview

The Generic InSAR Analysis Toolbox (GIAnT) is a suite of commonly used time-series interferometry algorithms in a common Python framework. Improvements in synthetic aperture radar (SAR) interferometry over the past couple of decades allow accurate measurement of ground surface deformation with unprecedented spatial coverage. Various packages are available to compute one or several interferograms, e.g, ROI_PAC [Rosen et al., 2004a], DORIS [Kampes et al., 2003], the new ISCE [Rosen et al., 2011], GMTSAR [Sandwell et al.] or variants, like NSBAS [Doin et al., 2011]. Observing large amplitude deformation signals, such as surface deformations due to earthquakes, is now a routine process. However, the detection of lower amplitude signals, such as interseismic accumulation, creeping faults, seasonal subsidence, etc., is more challenging. Time series analysis methods are used to enhance the signal-to-noise ratio and to study the temporal variability of surface deformation. The InSAR community uses a wide variety of methods and algorithms for interferometric time-series analysis. However, no common modular framework exists that allows researchers to quickly apply these wide range of algorithms on a single data set and compare their relative merits or limitations.

Development of GIAnT is primarily motivated by:

1. The need for standardization of data formats for ease in sharing time-series products.

2. Benchmarking of time-series InSAR algorithms.

3. Direct comparison of performance of various published algorithms.

4. A modular framework for efficient development of future time-series approaches.

GIAnT provides utility libraries of functions that are commonly used in various time-series approaches and includes demonstration scripts of various techniques. All the functions and scripts are documented in detail, allowing users to use these directly for data analysis or as building blocks for any time-series approach they would like to implement in the same framework.

1.2 Features

Some of key features of GIAnT include:

1. It is free.
2. It provides a Python-based framework.
3. Source code is distributed along with the package.
4. Use of memory mapped files facilitating analysis of large interferogram stacks.
5. A simple interface to weather model based atmospheric phase screen corrections [`http://earthdef.caltech.edu` Jolivet et al., 2011].
6. Direct calls to optimized linear algebra libraries like LAPACK, BLAS etc that can be optimized for speed using packages like ATLAS/ Intel MKL.
7. A set of interactive data visualization scripts.
8. Simple parallelization using Python's multiprocessing (shared memory) module for performance.

1.3 Algorithms

The time-series analysis routines in GIAnT can be broken down into two stages - spatial analysis and temporal analysis. GIAnT users can choose to analyze their data sets in radar (range, azimuth) coordinates directly or transform their data into wavelet domain before analysis. For the temporal analysis, the users can choose to work with the traditional piece-wise linear SBAS formulation [Berardino et al., 2002] or use a parameterized functional form of their choice [Hetland et al., 2011]. GIAnT modules have

been designed in a manner that allows users to combine various types of spatial and temporal analysis algorithms as desired. The following time-series techniques have already been implemented and are provided with GIAnT for immediate use.

1. Small Baseline Subset (SBAS) [Berardino et al., 2002].
2. N-SBAS [Lopez-Quiroz et al., 2009, Doin et al., 2011, Jolivet et al., 2012].
3. Multiscale Insar Time-Series (MInTS) [Hetland et al., 2011].
4. Timefn (Temporal analysis part of MInTS applied directly in data domain).

1.4 Programming philosophy

GIAnT consists of two types of programs - modules and scripts. In GIAnT, modules are building blocks combined in a preferred order within a script. We use modules to implement processing steps that are common to various time-series techniques. We have consciously chosen to implement the various time-series algorithms as scripts for ease of understanding. We expect that most of the end users will not be expert programmers and the processing flow should be easy to comprehend by studying the scripts directly.

Even though we want to keep an eye on the evolution of the future versions of GIAnT, these tools are OpenSource, and therefore, we accept, with great pleasure, any contributions you could make to add algorithms, improve existing routines or develop new methods.

1.5 Future work

This first release of GIAnT focuses on building a framework and implementing some of the basic time-series InSAR algorithms. The package will constantly be maintained and updated. Bug reports and fixes can be reported on the website `http://earthdef.caltech.edu`. GIAnT in its current form does not address all aspects of time-series InSAR and the future versions are expected to address the following issues:

1. The processing chain is expected to start with wrapped data. Phase unwrapping will be included as a processing step. If starting with

unwrapped data, consistency checks will be incorporated to identify unwrapping errors.

2. Algorithms for estimation of DEM Error in the wrapped domain that are already available in the public domain [e.g, Hooper et al., 2007, Ducret et al., 2011] will be incorporated into GIAnT.

3. Tidal load corrections [DiCaprio and Simons, 2008] will be included as a package similar to the atmospheric corrections. This component will be important for the analysis of coastal regions and continental scale data sets.

4. Incorporation of Persistent Scatter algorithms [e.g, Hooper et al., 2007, Shanker and Zebker, 2007, Hooper, 2008].

5. Inclusion of more complete error covariance models and propagation of uncertainty estimates through various stage of time-series InSAR processing.

6. Optimization of various algorithms, including the option of analysis on distributed systems.

Chapter 2

Installation

Most of GIAnT consists of python programs that just need to be copied to a specified location. We include a simple Python setup script for components of GIAnT that are in Fortran or C. A large number of other Python modules need to be installed in order for GIAnT to work on your machine. Installing these pre-requisites are relatively easy.

Generic Linux
We recommend using a package manager like apt or yum to install the pre-requisites before installing GIAnT. We provide command lines to install the required Python libraries on a Linux Ubuntu machine.

OS-X
A convenient way to install all the pre-requisites is to use the package manager MacPorts (free)[1]. Installing MacPorts on OS-X machines is straightforward but requires Xcode[2] (free). We provide command lines to install the required Python libraries using MacPorts. Please be sure to run these commands as root. Another package manager called Fink is available[3] but the installation of all the libraries required by GIAnT has never been tested with Fink.

[1] `http://www.macports.org`
[2] `https://developer.apple.com/xcode/`
[3] `http://www.finkproject.org`

2.1 Pre-requisites

All the following pre-requisites may be installed from source. Although, we strongly advise the use of a package manager for beginners.

2.1.1 Python 2.6 or higher

GIAnT uses Python (`http://www.python.org`) and you will need a minimum of Python 2.6, for various pre-requisite packages to work seamlessly. If for some reason, you choose to build Python from source, please ensure that you use the same set of compilers for building any of the other packages for Python. Also ensure that you get the development package for Python for Linux.

On OS-X, all required libraries for GIAnT are available on MacPorts, for Python 2.6 or Python 2.7. The suggested commands are for Python 2.7 but can de adapted by changing "27" to "26" in the commands.

```
Ubuntu - 12.04:
>> apt-get install python2.7 python2.7-dev

OS-X:
>> port install python27
>> port select python python27
```

2.1.2 Numerical Python (NumPy)

GIAnT makes extensive use of NumPy (`http://numpy.scipy.org`) for representing datasets as arrays and for many array manipulation routines. We also use some FFT and linear algebra routines provided with NumPy. numpy.int, numpy.float and numpy.float32 are the most common data formats used at various stages of processing arrays and data.

```
Ubuntu - 12.04:
>> apt-get install python-numpy

OS-X:
>> port install py27-numpy
```

If you want to improve the performance of Numpy, we suggest using LAPACK, BLAS and ATLAS libraries. For more details on installing numpy from source using these libraries, see `http://docs.scipy.org/doc/numpy/`

user/install.html. On OS-X, a variant of Numpy that includes LAPACK, BLAS and the optimization ATLAS libraries is available on MacPorts. We suggest users to install the variant including compilation by gcc 4.5:

```
OS-X:
>> port install py27-numpy +atlas +gcc45
```

2.1.3 Scientific Python (SciPy)

SciPy (http://scipy.org) contains many functions for linear algebra operations, FFTs and optimization. SciPy also includes support for sparse matrices and provides solvers for various types of optimization problems.

```
Ubuntu - 12.04:
>> apt-get install python-scipy

OS-X:
>> port install py27-scipy
```

Vanilla distributions of SciPy obtained through utilities like yum and apt are typically not optimized. For best performance on large Linux computers, SciPy must be compiled with ATLAS / Intel MKL support. On Apple computers, the optimized SciPy distribution can be installed by typing:

```
OS-X:
>> port install py27-scipy +atlas +gcc45
```

2.1.4 Cython

Cython (http://www.cython.org) is a language that makes writing C extensions for the Python language as easy as Python itself. Cython is ideal for wrapping external C libraries and for writing fast C modules that speeds up the execution of Python code.

```
Ubuntu - 12.04:
>> apt-get install cython
(or)
>> easy_install cython

OS-X:
```

```
>> port install py27-cython
(or)
>> easy_install cython
```

2.1.5 Matplotlib

Matplotlib (`http://matplotlib.sourceforge.net`) is a python 2D plotting library which produces publication quality figures in a variety of hardcopy formats and interactive environments across platforms. We use matplotlib for displaying output and for our interactive time-series viewers.

```
Ubuntu - 12.04:
>> apt-get install python-matplotlib

OS-X:
>> port install py27-matplotlib
```

2.1.6 h5py

h5py (`http://code.google.com/p/h5py`) provides a NumPy interface to Hierarchial Data Format 5 (HDF5) memory mapped files. We use h5py for storage and retrieval of named variables during various stages of processing. A big advantage of h5py is it allows us to access slices of large matrices directly from a file, without having to use up memory resources needed to read the entire matrices. The latest version of MATLAB also uses the HDF5 format and it is possible to directly read in .mat files into Python using scipy.io.loadmat.

```
Ubuntu - 12.04:
>> apt-get install python-h5py

OS-X:
>> port install py27-h5py
```

2.1.7 pygrib

GIAnT can directly interact with PyAPS modules to use weather model data for atmospheric phase screen corrections. pygrib (`http://code.google.com/p/pygrib`) provides the interface for directly reading in GRIB-format weather data files in Python. Successful installation of pygrib needs grib_api, openjpeg, jasper, libpng, zlib (including all development versions) which can

all be obtained using standard repository management tools. Pygrib also needs the basemap or pyproj module for python to be installed.

```
Ubuntu - 12.04:
>> apt-get install zlib1g zlib1g-dev
>> apt-get install libpng12-0 libpng12-dev
>> apt-get install libjasper1 libjasper-dev
>> apt-get install libopenjpeg2 libopenjpeg-dev
>> apt-get install libgrib-api-1.9.9 libgrib-api-dev libgrib-api-tools
>> apt-get install python-mpltoolkits.basemap
>> apt-get install pyproj
>> easy_install pygrib
```

Unfortunately, pygrib is not directly available using a package manager on all Linux machines. You will have to follow instructions on the Google code page to install pygrib after installing all the required packages.

On OS-X computers, you can install pygrib using macports (all the dependencies will follow with that command):

```
OS-X:
>> port install py27-pygrib
```

2.1.8 pywavelets

The MInTS Hetland et al. [2011] time-series approach uses wavelets for spatial analysis. We provide our own Meyer wavelet library for analysis with the original MInTS approach. However, GIAnT also allows one to use other wavelets for spatial decomposition of unwrapped interferograms using the pywt (`http://github.com/nigma/pywt`) package.

```
Ubuntu - 12.04:
>> apt-get install python-pywt

OS-X:
>> port install py27-pywavelets
(or)
>> easy_install pywavelets
```

2.1.9 LXML

GIAnT uses XML files for setting up data and processing parameters. Specifically, we use the eTree module from lxml to construct input XML

files and the objectify module from lxml to read in XML files. LXML (`http://lxml.de`) should be available as a standard repository on most linux distributions.

```
Ubuntu - 12.04:
>> apt-get install python-lxml

OS-X:
>> port install py27-lxml
```

2.2 Optional

We would also recommend installing the following packages before installing GIAnT.

2.2.1 ffmpeg or mencoder

We will need one of the two packages to use the matplotlib.animation submodule for making movies.

```
Ubuntu - 12.04:
>> apt-get install ffmpeg mencoder

OS-X:
>> port install ffmpeg
```

Mencoder is not available through MacPorts (maybe through Fink).

2.2.2 pyresample

Pyresample is a Python package that allows for easy geocoding of swath data (interferograms etc). We use pyresample to generate movies in the geocoded domain. Pyresample can be downloaded from `http://code.google.com/p/pyresample/`. If pyproj is already installed on your machine, you can install pyresample using the command

```
Ubuntu - 12.04 and OS-X:
>> easy_install pyresample
```

2.2.3 HDFview

HDFview is open source software for exploring the contents of an HDF file. The latest version can be downloaded from `http://www.hdfgroup.org/hdf-java-html/hdfview/index.html`.

```
Ubuntu - 12.04:
>> apt-get install hdfview
```

HDFview does not exist through MacPorts but can be easily installed following the instructions on the HDFview website.

2.2.4 iPython

Interactive Python (iPython) [Pérez and Granger, 2007] provides a rich toolkit for Python that allows users to work with the python interpreter in an environment similar to MATLAB or IDL.

```
Ubuntu - 12.04:
>> apt-get install ipython

OS-X:
>> port install py27-ipython
```

2.2.5 bpython

bpython `http://bpython-interpreter.org/` is a simple interface to the python interpreter. We recommend bpython when iPython cannot be used, for example when you are on a NFS partition.

```
Ubuntu - 12.04:
>> apt-get install bpython

OS-X:
>> port install py27-bpython
```

2.2.6 pykml

pykml (`http://packages.python.org/pykml/`) is a Python library for creating, parsing and manipulating KML files. GIAnT can output time-series products to KML files for immediate visualization in Google Earth.

```
Ubuntu - 12.04 and OS-X:
>> easy_install pykml
```

2.2.7 ImageMagick

This is typically a part of the standard Linux distributions. We use ImageMagick's **c**onvert utility to make parts of PNG files transparent for display usign KML/KMZ files.

```
Ubuntu - 12.04:
>> apt-get install imagemagick

OS-X:
>> port install imagemagick
```

2.2.8 xmlcopyeditor

xmlcopyeditor `http://xml-copy-editor.sourceforge.net/` is a simple editor for XML. The XML files used in GIAnT or ISCE can be easily modified using a text editor but xmlcopyeditor makes the task a little simpler. We recommend installing the package from source.

2.3 Installation

GIAnT has the following directory structure.

```
GIAnT (INSTALL directory)
|
|---- tsinsar   (Time-series library)
|
|---- pyaps     (Atmospheric corrections)
|
|---- SCR       (Time-series analysis scripts)
|
|---- geocode   (Geocoding library and scripts)
|
|---- solvers   (Solvers)
|
|---- setup.py  (Installation script)
|
|---- setup.cfg (Setup configure file)
```

Identify the directory in which you want to install **GIAnT** and make it your current working directory. Checkout the latest version of the code as

```
svn co http://earthdef.caltech.edu/svn/giant
cd giant/GIAnT
svn co http://earthdef.caltech.edu/svn/pyaps
```

Do not move the contents of the repository directory to another location as that may affect automatic updating of the repository using svn in the future. C and Fortran modules need to be built using C and Fortran compilers (see Section 2.3.1). The final step is to include the full path of the **giant/GIAnT** directory to the environment variable **PYTHONPATH**. This will allow python to import these modules whenever they are used in any script.

```
Using Bash:
>> export GIANT=/directory/where/you/did/copy/GIAnT
>> export PYTHONPATH=$GIANT:$PYTHONPATH

Using Csh:
>> setenv GIANT '/directory/where/you/did/copy/GIAnT'
>> setenv PYTHONPATH $GIANT:$PYTHONPATH
```

These commands should be included in your .bashrc or .cshrc files.

2.3.1 Building extensions

The setup script builds the **gsvd** module which contains our interface to the generalized SVD decomposition from LAPACK, similar to SciPy's interface to LAPACK and BLAS in this directory. The gsvd is used for L_2 norm regularized inversions in GIAnT.

The default settings uses the default C and fortran compilers to build extensions. The setup.cfg file can also be modified to force the machine to use a specific fortran compiler. If you have multiple Fortran and C compilers on your machine, you should specify the version compatible with your installation of python as shown below:

```
>>CC=Compiler python setup.py build_ext
--fcompiler=compiler-options
```

On OS-X, the default compiler will be clang. This will cause some problems if you use any regularized inversions. Therefore, on OS-X, if you

linked Numpy and Scipy to Atlas, as mentioned previously, you want to compile gsvd using:

```
>> CC=gcc-mp-4.5 python setup.py build_ext
 --fcompiler=gnu95
```

The compiler options can also be included in the setup.cfg file before executing setup.py .

If your LAPACK/BLAS libraries were not built with gfortran, readup on the "–fcompiler" option for numpy distutils.

Alternate installation
Alternately, identify the directories in which the LAPACK, BLAS and ATLAS libraries are located. Compile using f2py in the gsvd directory.

```
>> f2py gensvd.pyf dggsvd.f -LPATH_TO_LIBS -llapacklib
     -lblaslib -latlaslib

On Ubuntu - 12.04:
>> f2py gensvd.pyf dggsvd.f -llapack -lblas -latlas
```

Test the compiled module using the provided test.py. Ensure that you are using the f2py corresponding to the numpy version you want to use.

2.3.2 Non-standard installations

If you happened to install any of the above pre-requisite libraries yourself and if they are not located in the Standard library directories for your OS, include the paths to the shared object files (libxxxxxxxxx.so) to the environment variable **LD_LIBRARY_PATH**. This set of tools has not been tested, or even installed, on Windows operated machines.

2.4 Automated installation of pre-requisites

We maintain a simple puppet (`http://puppetlabs.com/puppet/puppet-open-source`) script for automatic installation of pre-requisite software on an Ubuntu 12.04/ 12.10 machine at `http://earthdef.caltech.edu/boards/3/topics/74`. We hope that users will contribute similar scripts for other Linux distributions and make it available to other GIAnT users.

We also maintain a table of required packages for various OS and Linux distributions at `http://earthdef.caltech.edu/documents/4`. We again

hope that active users will contribute to this table and add support for other Linux distributions.

Chapter 3

Using GIAnT

GIAnT is distributed with implementations of SBAS [Berardino et al., 2002, Doin et al., 2011] and MInTS [Hetland et al., 2011] techniques. The prepackaged implementations are meant to work with outputs from ROI_PAC [Rosen et al., 2004b], ISCE [Rosen et al., 2011], DORIS [Kampes et al., 2003], GMTSAR [Sandwell et al.] or GAMMA [GAMMA Remote Sensing Research and Consulting AG, 2013]. In our description of the various processing steps, we used the term "stack" to denote a three-dimensional cube of data, the dimensions typically corresponding to range direction, azimuth direction and either number of interferograms or SAR acquisitions. Our usage of the term "stack" should not be interpreted as some form of velocity estimate. Figure 3.1 describes the work flow in the current implementation of various time-series InSAR algorithms implemented in GIAnT. However, the main strength of GIAnT lies in its modular implementation of the algorithms which allows users to implement their own version of the different time-series techniques and to extend GIAnT. As shown in Figure 3.1, there are multiple stages in the analysis:

1. **Stack preparation**
   Unwrapped interferograms are read from various locations on disk and are consolidated into a data cube. The data cube is stored along with other auxiliary information in a hierarchical data format (HDF5) file. Chapter 4 describes this step in detail.

2. **Stack preprocessing**
   Preprocessing of the stack including orbit deramping and topo-correlated atmospheric phase correction. The outputs are stored in a HDF5 file. Chapter 5 describes each of the preprocessing steps in detail.

3. **Time-series estimation**
   The time-series is estimated from the processed stack using a technique of choice. Currently, you can choose between various SBAS techniques (Chapter 6) and MInTS (chapter 7).

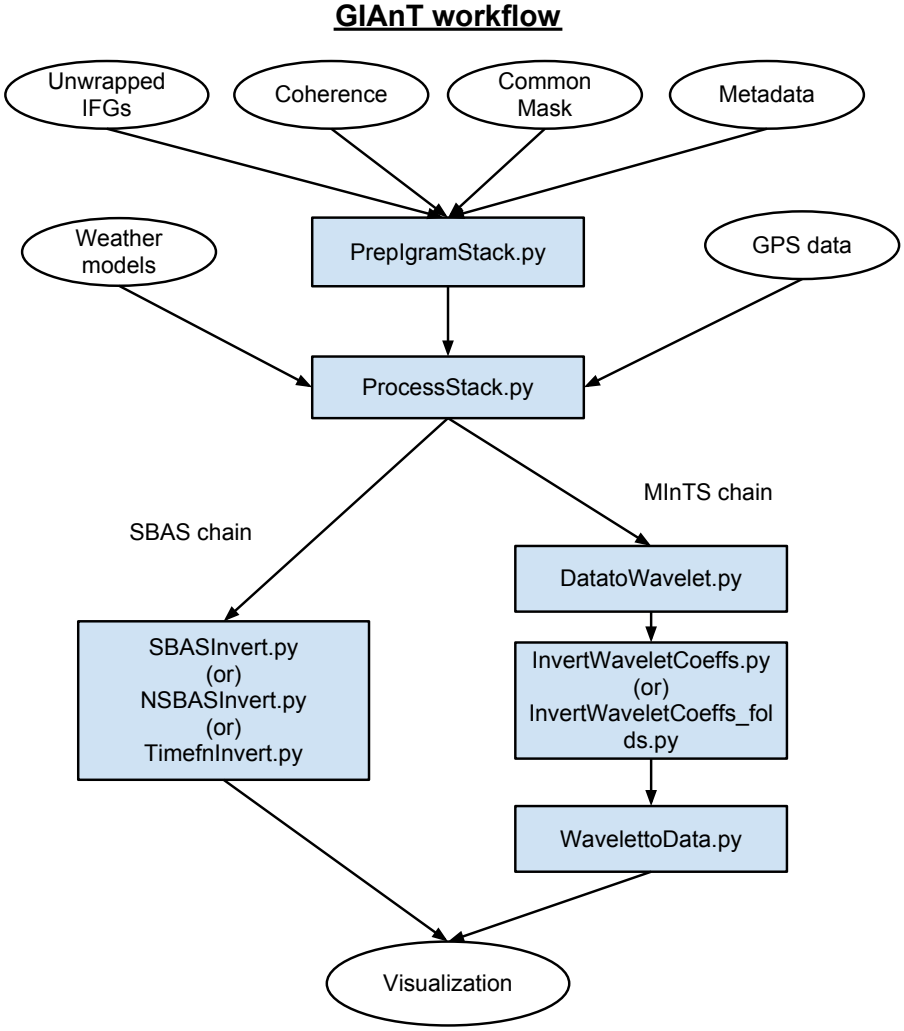

Figure 3.1: GIAnT workflow for using InSAR time-series analysis. The main strength of GIAnT is the modular implementation of these various stages. The modules can themselves be used to extend GIAnT and implement other time-series techniques.

Before processing any data, we strongly advise the users to familiarize themselves with various features of GIAnT, that will help them use the

toolbox more effectively.

3.1 Python

For users who are familiar with MATLAB or IDL, the transition to Python should be fairly easy. Two resources that we recommend for users who are new to Python are

- The tentative Numpy turorial- `http://scipy.org/Tentative_NumPy_Tutorial`
- Numpy for MATLAB users `http://mathesaurus.sourceforge.net/matlab-numpy.html`

3.2 Working with HDF5

The Hierarchical data format (HDF) allows us to save large amounts of data in an organized and easy to access manner. GIAnT uses HDF5 files in the same way that users use .mat files in MATLAB or .sav files in IDL. In GIAnT, all HDF5 files and the datasets they contain are stored with a "help" attribute. We recommend that the users become familiar with the h5py [Collette, 2008] module interface in Python for reading and displaying data sets using matplotlib. A good introductory tutorial can be found at `http://h5py.alfven.org/docs-2.0/intro/quick.html`.

To determine the overview of the contents of a HDF5 file, use

```
####Overview description of file
$ h5dump -a help Filename.h5
```

To determine the contents of the HDF5 and their description

```
#####List contents
$ h5ls Filename.h5

#####List contents with description
$ h5ls -v Filename.h5 | grep Data
```

To dump an array from HDF5 to a binary file, use **h5dump**. This command can also be used to crop the array before writing it to a file. HDFview is another tool that we strongly recommend for browsing through the contents of a HDF file.

3.3 Matplotlib

GIAnT uses matplotlib [Hunter, 2007] for plotting. Some familiarity with matplotlib will allow users to write their own visualization codes for debugging and understanding the processing chain. Two useful tutorials can be found at

- `http://matplotlib.sourceforge.net/users/pyplot_tutorial.html`
- `http://matplotlib.github.com/users/image_tutorial.html`

3.4 GIAnT conventions

Various processing stages in GIAnT conform to few simple rules.

Units The unwrapped interferograms are converted to millimeters (mm) before any preprocessing. The atmospheric phase screen from PyAPS and GPS data are also converted to millimeters.

Master-slave Typically, users prefer to use the most recent amongst the pair of SAR acquisitions as the master scene when generating interferograms. GIAnT has been designed to be flexible and automatically figures out the correct connectivity matrix even if the order of master and slave acquisitions do not adhere to a consistent convention. We would still recommend the users to the latest SAR acquisition as the master scene in every pair consistently.

Ground-to-satellite The line-of-sight direction corresponds to the vector from ground position to the satellite. All the estimated time-series products are always estimated with respect to the ground, i.e, in the case of purely vertical deformation positive values represent uplift and negative values represent subsidence.

Angles The incidence angle provided by the user as a file or as a constant input is always measured with respect to the ground. This information is used for projecting estimated atmospheric path delays and GPS data along the line-of-sight.

Help attributes All the metadata values in input XML files must include a `<help>` field. All datasets in HDF5 files must be stored with a help attribute. This requirement is designed to aid users in understanding the relevance of input, output and intermediate products.

Chapter 4

Preparing data for processing

During this first step of the processing, all the necessary metadata and the unwrapped interferograms are sorted and organized into an HDF5 file and a few additional binary files, specially formatted for GIAnT. Inputs are data from outputs of ROI_PAC, DORIS, GMTSAR, GAMMA or ISCE. As we would like to provide the most generic toolbox, we tried to implement readers for the most common datasets, but slight changes might be needed to adapt GIAnT to your case. In this section we describe how to use two scripts located in `GIANT/SCR`:

- **prepxml_SBAS.py** and **prepxml_MInTS.py** create the XML files needed to specify processing options to GIAnT.
- **PrepIgramStack.py** reads the input data and creates files for GIAnT.

4.1 Inputs

To run these steps, the user needs to gather the following files:

- The unwrapped interferograms in radar coordinates (range, azimuth) and in radians produced by ROI_PAC, DORIS, GMTSAR, GAMMA or ISCE. If the users have geolocated unwrapped interferograms that they wish to analyze, they should take a look at Section 4.1.1 before proceeding.
- The corresponding coherence files.

- A list of the Interferograms, with the perpendicular baseline and the sensor code name.
- A Radar simulation file containing the pixels elevation, i.e, the DEM in radar coordinates. If you are using a processor other than ROI_PAC, you will have to generate a ROI_PAC style rsc file including the approximate latitude and longitude values for the four corners (see Appendix A). This information is needed for subsetting weather model data.
- An example.rsc file(ROI_PAC) (or) interferogram.out and master.res files (DORIS) (or) insarProc.xml file (ISCE) or image.PRM and unwrap.grd files (GMTSAR) (or) date.mli.par (GAMMA).
- Optional: Two files containing each pixels latitude and longitude (binary files, same size as the interferograms, real single precision). These files can be GRD files in the case of GMTSAR.
- Optional: A mask file (binary file, same size as the interferogram, real single precision, 0 for False, 1 for True). This file can be a GRD file in case of GMTSAR.

We use the following setup for processing time-series with GIAnT. It is relatively simple to modify the stack[1] preparation script to use a different setup if desired. We pass the list of interferograms as an ASCII with four columns: the two first columns are the interferograms dates of acquisition coded over 6 or 8 digits (yymmdd or yyyymmdd), the third one is the perpendicular baseline while the last one is the sensor code name. Please make sure that the perpendicular baselines specified in here are consistent within the interferometric network, otherwise, the implemented Digital Elevation Model error estimation will produce incorrect results. A little example:

```
030104 031011 -384.6568006539 ENV
030104 031220 -412.2747552730 ENV
030104 041204 -346.6693732534 ENV
19920917 19920604 -158.938138675459 ERS
19921126 19920604 -194.461966044758 ERS
19921126 19920917 -35.4173555703392 ERS
....
```

You can optionally not provide the sensor name if you are using data from a single satellite. If you choose to mix data from multiple sensors, please

[1] Three-dimensional dataset and not a velocity estimate

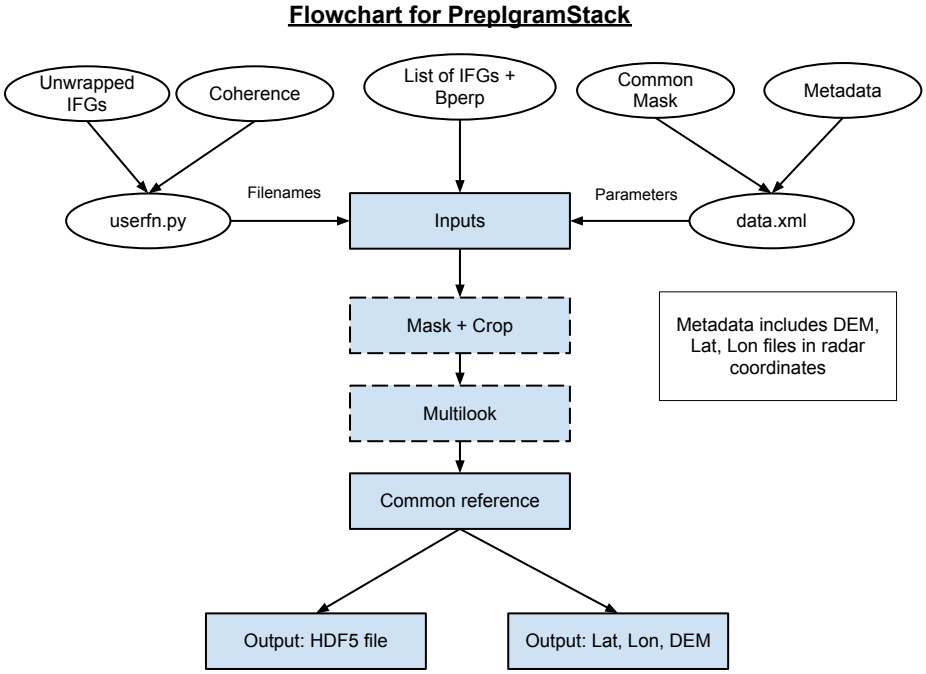

Figure 4.1: Work flow for preparing an interferogram stack.

ensure that the corresponding wavelength fields are populated in the **rdict** dictionary in **PrepIgramStack.py**. If all data is from a single sensor, the wavelength is automatically read in from the example rsc file. You will also need to provide a mapping from the dates to a filename on disk as a python function (Section 4.5).

We would also like to point out that most users will probably end up customizing the **P**repIgramStack.py script according to their own needs. Some users may prefer to read in the filenames and the associated wavelengths directly from an ASCII file. Implementing such changes should be trivial and we leave it up to the users to implement their favorite strategy.

4.1.1 Using geocoded stacks [1]

If the users have processed their interferograms individually and plan to combine them in geocoded domain, they should make the following changes to make GIAnT treat the data as if it was radar coded (range, azimuth).

1. Create latitude and longitude files of the same size as your geocoded unwrapped interferograms.

2. Crop your DEM to the same size as your geocoded unwrapped interferograms.

3. Make sure that undefined data is set to NaN in **PrepIgramStack.py** where the interferograms are read into a HDF5 file.

4. You will also need to include entries for the four corners of the DEM in a ROI_PAC style RSC file. See Appendix A.

4.2 Outputs

A HDF5 file containing the following datasets is computed:

- `Jmat`: Matrix linking the interferograms to the acquisition dates, made of 0, 1 and -1.
- `bperp`: Vector of the perpendicular baseline values.
- `cmask`: Mask map of the pixels.
- `dates`: Dates of acquisition.
- `tims`: Time of acquisition in the specific ordinal reference.
- `usat`: Satellite sensor code name.
- `igram`: 3D matrix of size $n \times l \times w$, where n is the number of interferograms, l and w are the interferograms length (number of pixels along azimuth) and width (number of pixels along range).

Additionally, the binary files containing each pixels latitude, longitude and elevation are also output if the corresponding inputs are provided. Finally, PNG format previews of the interferograms are created.

4.3 Directory structure

The first step is to create a working directory. The sub-directories are automatically created as needed by the different scripts. The default file and directory names can be modified by the different scripts if needed. The typical structure of the working directory is:

```
|-Working directory (Xml + scripts + metadata)
|
|---Figs
|   |
|   |----- Igrams (Raw interferograms)
|   |
|   |----- Atmos  (Atmospheric corrections)
|   |
|   |----- Ramp   (Deramped)
|
|---Stack (All the h5 files)
|
|---Atmos (All the weather model data)
|
|---RESP (Wavelet Impulse Response, Only if you use MInTS)
```

4.4 Preparing XML files

The inputs to the SBAS and MInTS scripts are controlled using XML files. We currently use three XML files - one for data parameters (**data.xml**), one for the processing parameters of SBAS style chains (**sbas.xml**) and one for processing parameters of MInTS (**mints.xml**). An example of these files can be found in the `GIAnT/example` directory and in the Appendices.

These XML files are prepared using the **prepxml_SBAS.py** or the **prepxml_MInTS.py** scripts. These scripts can be modified to add additional processing parameters as desired. The parameter values in the XML files should be modified as per requirement and the processing strategy. In the following, we describe the possible options included. Currently, the scripts are designed to work with data in radar (range, azimuth) coordinates. The XML files produced by the **prepxml_XXXX.py** scripts can also be modified in a text editor.
To run these scripts, type:

```
>> python prepxml_SBAS.py
```

or

```
>> python prepxml_MInTS.py
```

Note that the structure of the XML files changes as we add more options to the processing chain and need more control parameters. The help fields

in the XML files have been added to describe each of the options for the benefit of users.

4.4.1 Writing the data.xml file

Both **prepxml_XXXX.py** scripts start by writing the XML file corresponding to your dataset (data format, additional looks, crop region etc). In the scripts, these parameters are parsed through the routine `prepare_data_xml`. You should modify the arguments of this routine according to your needs. For the data to be read in successfully, a meaningful reference region has to be provided. If a reference region is not provided, average bias is corrected from each interferogram.

The syntax is:

```
prepare_data_xml(self, fname, proc='RPAC',looks=1,
cohth=0.0, mask='',xlim=None, ylim=None,
rxlim=None, rylim=None, latfile='',
lonfile='', hgtfile='', inc=23.0, h5dir='Stack',
atmosdir='Atmos', figsdir='Figs', respdir='RESP',
unwfmt='RMG', demfmt='RMG', corfmt='RMG',
chgendian=False, endianlist=['UNW','COR','HGT']),
masktype='f4')
```

The only non-optional argument is:

- **fname** - The name of the example rsc file from ROI_PAC. This file contains parameters like the width of the image, its length, the sensors wavelength.... An example can be found in the directory `GIAnT/example`.

. The optional arguments are:

Param	Type	Help	Default
proc	STR	Processor used for generating the interferograms. Can be RPAC, DORIS, ISCE, GAMMA or GMT.	RPAC
looks	INT	Number of additional looks. No looks is default.	1
cohth	FLOAT	Coherence threshold for SBAS pixel selection. This parameter allows to throw out pixel with a coherence value lower than **cohth**. No pixels are rejected by default.	0.0

mask	STR	File for common mask for pixels. This mask has to be the same size as your interferograms, and consist on a binary grid of 1 and 0 or NaN.	None
file_length	INT	Number of azimuth lines in the unwrapped files	From rsc file
width	INT	Number of range pixels in the unwrapped files	From rsc file
xmin	INT	First pixel of cropping limit in Range direction	None
xmax	INT	Last pixel of cropping limit in Range direction	None
ymin	INT	First line of cropping limit in Azimuth direction	None
ymax	INT	Last line of cropping limit in Azimuth direction	None
rxmin	INT	First pixel of reference region in Range after cropping	None
rxmax	INT	Last pixel of reference region in Range after cropping	None
rymin	INT	First line of referene region in Azimuth after cropping	None
rymax	INT	Last line of reference region in Azimuth after cropping	None
latfile	STR	Latitude file. The latitude file is a binary file, that has the same size as your interferograms, that specifies the latitude of each pixel. It is encoded has real, single precision. If this file is not provided, then, GIAnT uses a crude and simple linear transformation to calculate the geographic coordinates of the pixels. This is needed only by the PyAPS module. If you specify a latfile, you need to specify a lonfile.	None

lonfile	STR	Longitude file. The longitude file is a binary file, that has the same size as your interferograms, that specifies the latitude of each pixel. It is encoded has real, single precision. If this file is not provided, then, GIAnT uses a crude and simple linear transformation to calculate the geographic coordinates of the pixels. This is needed only by the PyAPS module. If you specify a lonfile, you need to specify a latfile.	None
hgtfile	STR	Altitude file. The hgt file is a RMG file (ROI_PAC style) or a binary file, that has the same size as your interferograms. It specifies the altitude, in meters, of each pixels.	None
inc	FLOAT (or) STR	Incidence angle. Can be a constant or a file of the same dimensions as lat/lon. Used only by PyAPS.	23.0^o.
h5dir	STR	Directory where all the HDF5 files will be stored.	`./Stack`
atmosdir	STR	Directory where all the atmospheric data will be stored.	`./Atmos`
figsdir	STR	Directory where all the figures will be stored.	`./Figs`
respdir	STR	Directory where the Impulse response for wavelet transform are stored (MInTS case).	`./RESP`
unwfmt	`RMG`/`FLT`	Specifies the format of the interferogram files. `RMG` is the standerd ROI_PAC output for unwrapped interferograms (real, single precision, amplitude and phase). `FLT` is a simple binary file (real, single precision).	`RMG`
demfmt	`RMG`/`FLT`	Specifies the format of the Digital Elevation Model file.	`RMG`
corfmt	`RMG`/`FLT`	Specifies the format of the correlation files.	`RMG`
chgendian	BOOL	Swaps bytes if true for the file types specified in the **endianlist**	`False`
endianlist	List of STR	Specifies the file type concerned by byte swapping if **chgendian** is `True`.	'UNW', 'COR', 'HGT'

masktype	STR	Type of data in the provided mask file (optional) Can be any `dtype` used in Numpy.	`'f4'`

4.4.2 Writing the sbas.xml file

If you intend to use any of the three SBAS style methods provided here, you will need to create a **sbas.xml** file by modifying the script **prepxml_SBAS.py** according to your needs. The informations about your processing strategy are parsed through the routine `prepare_sbas_xml`. The syntax is:

```
prepare_sbas_xml(self, netramp=False, atmos='', demerr=False,
nvalid=0, regu=False, masterdate='', filt=1.0, gpsramp=True,
stnlist='', stntype='', gpspath='', gpstype='', gpsvert=False,
gpspreproc=False, gpsmodel=False, unwcheck=False,
gpspad=3, gpsmin=5, tropomin=1, tropomax=None, tropolooks=8)
```

The optional arguments are:

Param	Type	Help	Default
netramp	BOOL	Network deramping: True/False. Interferograms are flattened by estimating and removing a best fit ramp. The best fit ramp parameters are re-estimated in a network sense. For more details, refer to section 5.4.1.	False
gpsramp	BOOL	GPS deramping: True/False. Interferograms are flattened using displacement informations from a GPS network.	False
atmos	STR	Atmospheric corrections: ECMWF/ERA/NARR/MERA/TROPO. The stratified component of the tropospheric is mapped from Global Atmospheric Models or estimated from the phase/elevation relationship (TROPO) and removed to the interferograms. For more details, refer to section 5.3.	None
demerr	BOOL	DEM Error estimation: True/False. Estimation of the Digital Elevation Model error during the Time Series analysis.	False

nvalid	INT	Minimum number of interferograms where a pixel is coherent. The pixel will be included in the Time Series analysis only if its coherence is higher than **cohth** in more than **valid** interferograms.	0
regu	BOOL	Regularization of time functions: True/-False. Activate the automatic determination of the regularization parameter in the Time Function inversion. For more details, refer to chapter 6.5.1.	False
masterdate	STR	Time to be used as reference (yyyymmdd). Default is the first date of the time series if not specified.	None.
stnlist	STR	Path to the GPS station list.	None
stntype	BOOL (or) STR	Code name for the type of station list. Can be True/ False/ velocity.	None
gpspath	STR	Directory where GPS data are stored.	None
gpstype	STR	Type of GPS file that can be used (sopac or velocity).	None
gpsvert	BOOL	Use the verticals of GPS data.	False
gpspreproc	BOOL	Preprocess GPS time series with splines.	False
gpsmodel	BOOL	Use the modeled GPS time series as input.	False
gpspad	INT	Half-width of the window around a GPS station.	3
gpsmin	INT	Minimum number of GPS stations per scene to proceed to the GPS de-ramping process. The process stops if less than `gpsmin` stations are found for one scene.	5
tropomin	INT	Minimum scale for empirical estimation of topography correlated atmosphere.	1
tropomax	INT	Minimum scale for empirical estimation of topography correlated atmosphere. If not defined, determined from dimensions.	None
tropolooks	INT	Number of looks to be applied to interferogram before empirical estimation of topography correlated atmosphere.	8

4.4.3 Writing the mints.xml file

If you intend to use the MInTS method, you will need to create a **mints.xml** file by modifying the script **prepxml_MInTS.py** according to your needs. The informations about your processing strategy are parsed through the routine `prepare_mints_xml.py`. The syntax is:

```
prepare_mints_xml(self, netramp=False, atmos='', demerr=False,
minscale=2, regu=True, masterdate='', minpad=0.1, shape=True,
smooth=3, skip=2, wvlt='meyer', gpsramp=True, stnlist='',
stntype='', gpspath='', gpstype='', gpsvert=False, gpspreproc=False,
gpsmodel=False, uwcheck=False, kfolds=1, lamrange=[-5,5,50],
tropomin=1, tropomax=None, tropolooks=8)
```

The optional arguments are:

Param	Type	Help	Default
netramp	BOOL	Network deramping: True/False. Interferograms are flattened by estimating and removing a best fit ramp. The best fit ramp parameters are re-estimated in a network sense. For more details, refer to section 5.4.1.	False
gpsramp	BOOL	GPS deramping: True/False. Interferograms are flattened using displacement informations from a GPS network.	False
atmos	STR	Atmospheric corrections: ECMWF/ERA/NARR/MERA. The stratified component of the tropospheric is mapped from Global Atmospheric Models and removed to the interferograms. For more details, refer to chapter 5.3.	None
demerr	BOOL	DEM Error estimation: True/False. Estimation of the Digital Elevation Model error during the Time Series analysis.	False
minscale	INT	Number of smallest scales (or) highest frequency components to be ignored during reconstruction.	1
maxscale	INT	Number of largest scales (or) smallest frequency components to be ignored during reconstruction.	0

regu	BOOL	Regularization of time functions: True/-False. Activate the automatic determination of the regularization parameter in the Time Function inversion. For more details, refer to chapter 6.5.1.	False
masterdate	STR	Time to be used as reference (yyyymmdd). Default is the first date of the time series.	None
minpad	FLOAT	Minimum amount of mirroring to be applied to images before converting to Dyadic length for wavelet transforms. Expressed as fraction of the width of the image.	0.1
shape	BOOL	Shape smoothing to be applied to the regularization matrix. See Hetland et al. [2011] for details.	False
smooth	INT	Spatial smoothing of the regularization parameter in k-fold cross validation.	3
skip	INT	Number of pixels to skip during estimation of the penalty parameters in k-fold cross validation. This reduces the execution time.	2
wvlt	STR	Name of the wavelet used for MInTS. Can be meyer or any valid string from pywt.	meyer
stnlist	STR	Path to the GPS station list.	None
stntype	BOOL (or) STR	Code name for the type of station list. Can be True/ False/ velocity.	None
gpspath	STR	Directory where GPS data are stored.	None
gpstype	STR	Type of GPS file that can be used (sopac or velocity).	None
gpsvert	BOOL	Use the verticals of GPS data.	False
gpspreproc	BOOL	Preprocess GPS time series with splines.	False
gpsmodel	BOOL	Use the modeled GPS time series as input.	False
gpspad	INT	Half-width of the window around a GPS station.	3
gpsmin	INT	Minimum number of GPS stations per scene to proceed to the GPS de-ramping process. The process stops if less than `gpsmin` stations are found for one scene.	5
kfolds	INT	Number of folds for k-fold cross validation in the MInTS inversions.	8

lamrange	LIST	Range of penalty parameter values to search across in logspace. First and second elements represent the min and max values in log space and the last values represents the number of steps.	[-5, 5, 50]
tropomin	INT	Minimum scale for empirical estimation of topography correlated atmosphere.	1
tropomax	INT	Minimum scale for empirical estimation of topography correlated atmosphere. If not defined, determined from dimensions.	None
tropolooks	INT	Number of looks to be applied to interferogram before empirical estimation of topography correlated atmosphere.	8

4.4.4 Writing more XML files

Another routine called `prepare_gen_xml` exists and can be easily modified to produce any XML file. Any other time series analysis method, radically different from the SBAS methods or the MInTS method provided here should include its own XML files and its own XML writer. Users are strongly encouraged to implement their own techniques and the associated XML file structure.

4.5 Preparing the Interferogram Stack

PrepIgramStack.py script is used to prepare the stack[2] of raw interferograms. We strongly encourage the user to copy this script in the working directory and to modify it according to the demands of the dataset. This script first reads the parameters in the **data.xml** file and the interferogram list in the **ifg.list** file. Then the script uses a user-defined function to map the interferogram dates to a physical file on disk. The function must be defined in a standalone python file called **userfn.py** (default). The users can start with the template provided in the example directory.

PrepIgram.py uses the user-defined function to read the unwrapped interferograms and the coherence files, crops them to the desired region, excludes the pixels with a coherence lower than **cohth**, removes the mean from the reference region and stores them in the output HDF5 file. It

[2]Three dimensional data set and not velocity estimates

finally formats the latitude, longitude, elevation and incidence (optional) files if provided.

You can run **PrepIgramStack.py** as follows:

```
>> python PrepIgramStack.py -h -i INAME -o ONAME -x DXML
                          -f FIGS -u USERPY
```

Like all the scripts included in GIAnT, using the `-h` flag as input provides a detailed description and input options for the script. The input options for **PrepIgramStack.py** are:

- **-h**: Ask for help.
- **-i INAME**: INAME Input file name containing interferograms acquisition dates, perpendicular baseline and sensor code name. Default is `ifg.list`.
- **-o ONAME**: ONAME Output HDF5 file name. Default is `RAW-STACK.h5`.
- **-x DXML**: DXML data.xml filename. Default is `data.xml`.
- **-f FIGS**: FIGS Directory in the general figure directory where interferograms previews are stored. Default is `Igrams`.
- **-u USERPY**: USERPY Python script with the user defined function `makefnames`.

PrepIgramStack.py currently supports RMG or plain binary files which are either in short, integer, float32 or float64 format. Any other format would require some additional changes in the **PrepIgramStack.py** script. The input formats for the files are read in from the **data.xml** file. If users develop readers for data in other formats, we strongly encourage them to share these with the community.

4.6 Checklist

Here is a summary of the actions and commands to prepare your dataset:

1. Create a working directory.
2. Gather the necessary files: interferograms, coherence files, radar simulation (DEM in radar coordinates) file, example.rsc/interferogram.out files, interferogram list, latitude and longitude files (optional), mask file (optional), incidence angle file (optional).

3. Copy to the working directory and modify the **prepxml_SBAS.py** or **prepxml_MInTS.py** files.
4. Run: `python prepxml_SBAS.py` or `python prepxml_MInTS.py`.
5. Copy **PrepIgramStack.py** to the working directory and modify it if needed.
6. Copy **userfname.py** to the working directory and modify it.
7. Run: `python PrepIgramStack.py [Options]`
8. Check that you have a new HDF5 file and have a look at the PNG previews just created.
9. If you provided lat, lon and incidence angle files as inputs make sure that equivalent binary files are created in the **h**5dir directory.

Chapter 5

Removing orbital ramps and stratified tropospheric artifacts

Once the data are has been read into a HDF5 file, the user may proceed to the stack pre-processing by applying atmospheric corrections and the estimation of residual orbit errors. These corrections are performed by the **ProcessStack.py** script. No major change is required in this script, unless the users wants to implement their own correction strategy. Again, we ask users to share their extensions of this script with the community.

ProcessStack.py uses the parameters provided in the **data.xml** and **sbas.xml** (default) or **mints.xml** files. It processes the data stored into the previously created HDF5 file (default: Stack/RAW-STACK.h5) and the latitude, longitude, elevation and incidence (optional) files. To execute, type:

```
>> python ProcessStack.py -h -i INAME -o ONAME -x DXML -p PXM
```

The command line options are:

- **-h**: Ask for help.
- **-i INAME**: INAME Input HDF5 file. Default is `RAW-STACK.h5`.
- **-o ONAME**: ONAME Output HDF5 file. Default is `PROC-STACK.h5`.
- **-x DXML**: DXML Data XML file. Default is `data.xml`.
- **-p PXML**: PXML SBAS/MInTS XML file. Default is `sbas.xml`.

5.1 Inputs

To run this script, the user needs to make sure the following files are available:

- The output HDF5 file from the **PrepIgramStack.py** script.
- The **sbas.xml** or the **mints.xml** files.
- The latitude, longitude, elevation and incidence (optional) files produced by the **PrepIgramStack.py** script.
- The password section of model.cfg in the pyaps directory to be filled out, if it is desired to used weather models for correcting stratified tropospheric delay.
- The GPS data files, as described below.

5.2 Outputs

The output is, by default, stored in the HDF5 file `Stack/PROC-STACK.h5`. The file name may be modified using the command line `-o` flag. This file contains the following datasets:

- `Jmat`: Matrix linking the interferograms to the acquisition dates, made of 0, 1 and -1.
- `bperp`: Vector of the perpendicular baseline values.
- `cmask`: Mask map of the pixels.
- `dates`: Dates of acquisition.
- `tims`: Time of acquisition in the specific ordinal reference.
- `figram/igram`: 3D matrix containing the corrected interferograms. Its size is $n \times l \times w$, where n is the number of interferograms, l and w are the interferograms length (number of pixels along azimuth) and width (number of pixels along range).
- `ramp`: Array of ramp parameters. Its size is $n \times p$ where n is the number of interferograms and p the number of ramp parameters per interferogram.

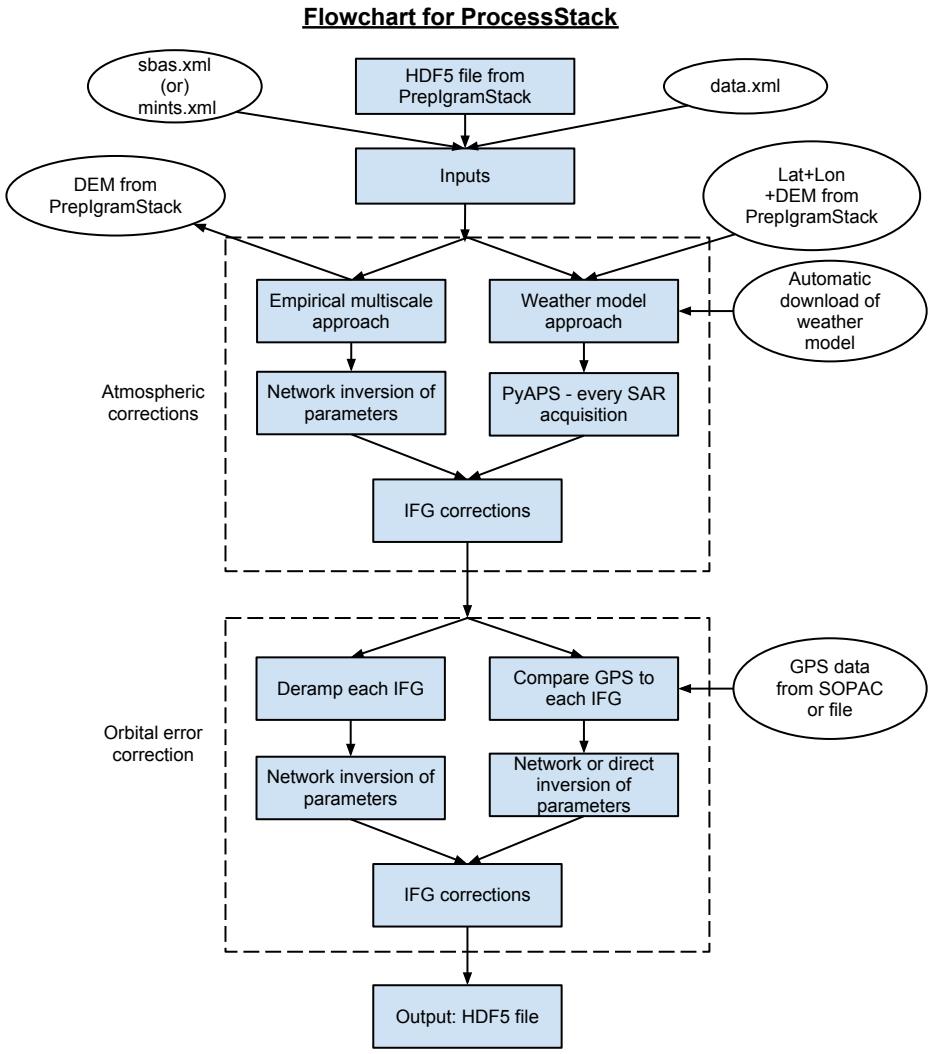

Figure 5.1: Work flow for processing an interferogram stack.

- `igram_aps`: Synthetic delay maps of each interferograms from the selected Global Atmospheric Model (Optional).

- `sar_aps`: Synthetic delay maps of each SAR acquisitions from the selected Global Atmospheric Model (Optional).

5.3 Atmospheric corrections

We use the PyAPS [Jolivet et al., 2011, Jolivet and Agram, 2012] module for implementing weather model based interferometric phase delay corrections. The python module is well documented, maintained and can be freely downloaded [1]. To use it in GIAnT, there is no need to download it as it is part of the package. PyAPS currently includes support for ECMWF's ERA-Interim, NOAA's NARR and NASA's MERRA weather models. The outputs from our processing modules include phase screen simulations for individual SAR scenes as well as phase corrections for each interferogram. PNG previews of the atmospheric corrections are saved (by default in the directory `Figs/Atmos`).

5.3.1 Theory and methodology

Following Doin et al. [2009] and Jolivet et al. [2011], we produce tropospheric delay maps from atmospheric data provided by Global Atmospheric Models. This method aims to correct differential atmospheric delay correlated with the topography in interferometric phase measurements. Global Atmospheric Models (hereafter GAMs), such as ERA-Interim (European Center for Medium-Range Weather Forecast), MERRA (Modern-Era Retrospective Analysis, Goddard Space Flight Center, NASA) or regional models such as NARR (North American Regional Reanalysis, National Oceanographic and Atmospheric Administration) provide estimates of the air temperature, the atmospheric pressure and the humidity as a function of elevation on a coarse resolution latitude/longitude grid. In PyAPS, we use this 3D distribution of atmospheric variables to determine the atmospheric phase delay on each pixel of each interferogram.

For a given GAM dataset, we select grid points overlapping with the spatial coverage of the SAR scene. Atmospheric variables are provided at precise pressure levels. We vertically interpolate these values to a regular grid between the surface and a reference altitude, z_{ref}, above which the delay is assumed to be nearly unchanged with time ($\sim$ 30000 m). We then compute the delay function on each of the selected grid points of the GAM as a function of height. The LOS single path delay $\delta \mathrm{L}^{s}_{LOS}(z)$ at an elevation

[1] `http://pyaps.googlecode.com`

z is given by [Doin et al., 2009, Jolivet et al., 2011]:

$$\delta \mathrm{L}^{s}_{LOS}(z) = \frac{10^{-6}}{cos(\theta)} \left\{ \frac{k_1 R_d}{g_m}(P(z) - P(z_{ref})) + \int_{z}^{z_{ref}} \left(\left(k_2 - \frac{R_d}{R_v} k_1 \right) \frac{e}{T} + k_3 \frac{e}{T^2} \right) dz \right\}, \tag{5.1}$$

where θ is the local incidence angle, $R_d = 287.05$ J.kg^{-1}.K^{-1} and $R_v = 461.495$ J.kg^{-1}.K^{-1} are respectively the dry air and water vapor specific gas constants, g_m is a weighted average of the gravity acceleration between z and z_{ref}, P is the dry air partial pressure in Pa, e is the water vapor partial pressure in Pa, and T is the temperature in K. The constants are $k_1 = 0.776$ K.Pa^{-1}, $k_2 = 0.716$ K.Pa^{-1} and $k_3 = 3.75 \cdot 10^3$ K^2.Pa^{-1}.

We compute the absolute atmospheric delay at each SAR acquisition date. For a pixel a_i at an elevation z at acquisition date i, we select the 4 surrounding grid points, 1, 2, 3 and 4. At each of these four grid points, we compute the delays at elevation z: $d^i_1(z)$, $d^i_2(z)$, $d^i_3(z)$ and $d^i_4(z)$. The resulting delay at the pixel a_i is the bilinear interpolation of $d^i_1(z)$, $d^i_2(z)$, $d^i_3(z)$ and $d^i_4(z)$. As the latitude/longitude grid of the NARR is based on a Lambert Conic sampling, we add a spatial linear resampling of the delay functions to match with a regular grid.

Finally, we combine the absolute delay maps corresponding to the SAR scenes to produce the differential delay maps used to correct the interferograms. Details and validation of our approach are available in Doin et al. [2009] and Jolivet et al. [2012].

5.3.2 Implementation and possible options

The script **ProcessStack.py** automatically downloads the atmospheric data into the directory `Atmos` (by default) before estimation the corrections to be applied to the interferograms. If the data has already been downloaded, it will not download it again. Each weather model has a different file naming convention, thus allowing users to determine the applicability and the effectiveness of different weather models on their interferogram stack[2]. PyAPS does not interpolate the weather model data in time and uses model information from the epoch closest to the SAR acquisition times. PyAPS can use three different GAMS (including automatic download) and the preferred model needs to be specified in the **sbas/mints.xml** file:

[2]Three dimensional dataset and not velocity estimates

- **ECMWF**: ERA-Interim Re-Analysis products are downloaded from the ECMWF repository in Europe[3] . We use the variables Temperature, Geopotential Height and Relative Humidity (default) at each Pressure Levels. If you are working on a machine with a non-US IP address, you should use this option. You need to register on the ECMWF website and provide your password in the file `GIAnT/pyaps/model.cfg` (a template is provided). Follow these steps to set up your access

  1. **Agree to terms and conditions**
     To get your personalized access key from ECMWF, by read and agree to this license `http://data-portal.ecmwf.int/data/d/license/interim_full/`.
  2. **Register**
     Register at `https://apps.ecmwf.int/registration/` with the same email address used to agree to the terms and conditions.
  3. **Login**
     Login at `https://apps.ecmwf.int/auth/login/`.
  4. **Sign the agreement**
     Sign the agreement at `http://apps.ecmwf.int/datasets/licences/general/`.
  5. **Copy your key to model.cfg** Obtain your API key from `https://api.ecmwf.int/v1/key/` and copy it to your model.cfg file.

  PyAPS only downloads the fields of interest from the ECMWF archive - Humidity and Temperature as a function of pressure level. Each file (global for single time eopch) is about 28MB in size.

- **ERA**: ERA-Interim Re-Analysis products are available from the repository hosted by the University Corporation for Atmospheric Research (UCAR), Boulder, CO, USA[4]. We use the variables Temperature, Geopotential Height and Relative Humidity (default) at each Pressure Levels. If you are located in the US, you can download the ERA-Interim data faster from the UCAR archives. You need to register on the ERA Interim page at the UCAR website and provide your password in the file `GIAnT/pyaps/model.cfg` (a template is provided). You will need to register for access to the ERA Interim full resolution data set here `http://rda.ucar.edu/datasets/ds627.0/`. Once you have an active registered login, scroll down to the bottom of the same

[3] `http://data-portal.ecmwf.int/`
[4] `http://rda.ucar.edu/`

webpage and click on data access. You will need to agree to the terms and conditions before proceeding. You might have to wait for a email confirming your access to the data set. This dataset can only be accessed from within the United States. Each file is about 89MB in size. Our scripts do not attempt to subset this dataset.

- **NARR**: NARR Re-Analysis product is downloaded from the repository hosted by the National Oceanic and Atmospheric Administration (NOAA), USA. We use the variables Temperature, Geopotential Height and Relative Humidity (default) at each Pressure Levels. NARR covers North America at a resolution of about 30 km and has a temporal resolution of 3 hours. The original data is distributed on a non-uniform grid. PyAPS computes delay functions on the original grid and reinterpolates these functions onto a regular lat-lon grid before estimating corrections. No special login is needed to access this dataset. Each file is about 56MB in size.

- **MERRA**: MERRA Re-Analysis product is downloaded from the repository hosted by the NASA Goddard Space Flight Center, USA[5]. We use the variables Temperature, Pressure level height and Relative humidity. No special login is needed to access this dataset.

Users are strongly encouraged to report on the effectiveness of GAMs, send us feedback on PyAPS or implement their own modules in PyAPS to share it with the community. More details can be found in the PyAPS manual available online. In future versions of GIAnT, we plan to provide direct access to OSCAR's atmospheric phase delay maps (Jet Propulsion Laboratory, NASA), produced by merging GAMs and MODIS (Moderate Resolution Imaging Spectroradiometer, NASA) measurements and third party GPS-based tropospheric corrections.

5.3.3 Empirical corrections

If users prefer assuming a simple linear relationship with topography, the stratified atmospheric phase contributions can be estimated from the data itself. We optionally provide an implementation of a multi-scale approach Lin et al. [2010b]. The atmos parameter in the XML file needs to be set to **TROPO**.

[5] `http://goldsmr3.sci.gsfc.nasa.gov`

5.4 Orbital errors estimation

Users are strongly encouraged to flatten the interferograms and correct for orbital errors prior to any time series analysis. We provide two methods for estimating orbital effects on interferograms, a network de-ramping and a GPS-based estimation method. If atmospheric corrections are activated, orbital errors will be estimated on corrected interferograms.

5.4.1 Network De-Ramping

This option is activated by setting the `netramp` parameter to `True` in the **sbas.xml** or **mints.xml** files. The process has been described by multiple studies, including Biggs et al. [2007], Cavalié et al. [2008], Lin et al. [2010a], Jolivet et al. [2012].

First, orbital errors are estimated independently on each interferogram using a least square scheme. By default, for the interferogram composed of two SAR acquisitions with indices i and j, we minimize the l_2 norm, $||d_{ij}(x,y) - R_{ij}(x,y)||_2$, where $d_{ij}(x,y)$ is the value of the pixel at range x and azimuth y, and

$$R_{ij}(x,y) = e_{ij} \cdot xy + a_{ij} \cdot x + b_{ij} \cdot y + c_{ij}, \tag{5.2}$$

where a_{ij}, b_{ij}, c_{ij} and e_{ij} are referred to as orbital parameters for the interferogram ij. The orbital term equation can be modified by changing the inputs of the `estramp` function in the **ProcessStack.py** script, so that,

$$\text{if poly} = 1, \qquad R_{ij}(x,y) = c_{i,j}, \tag{5.3}$$

$$\text{if poly} = 3, \qquad R_{ij}(x,y) = a_{ij} \cdot x + b_{ij} \cdot y + c_{ij}, \text{(default)} \tag{5.4}$$

$$\text{if poly} = 4, \qquad R_{ij}(x,y) = e_{ij} \cdot xy + a_{ij} \cdot x + b_{ij} \cdot y + c_{ij}. \tag{5.5}$$

Then, to ensure consistency in the interferometric network, we re-estimate the orbital parameters in a network sense. We estimate the orbital parameters for each SAR acquisition i, by inverting the linear systems given by,

$$a_{ij} = a_i - a_j, \tag{5.6}$$

$$b_{ij} = b_i - b_j, \tag{5.7}$$

$$c_{ij} = c_i - c_j, \tag{5.8}$$

$$d_{ij} = d_i - d_j. \tag{5.9}$$

Finally, we combine the re-estimated orbital parameters to produce orbital correction maps consistent with interferometric network and correct each interferogram. Other ramp functions can be easily incorporated in the `GIAnT/tsinsar/stackutils.py` file.

5.4.2 GPS De-Ramping

This option is activated by setting the `gpsramp` to `True` in the **sbas.xml** or **mints.xml** files. GPS velocities can be provided using a single ASCII file or in the SOPAC format. An example is available in the Appendices.

Theory

The GPS-based de-ramping technique starts by choosing the GPS stations overlapping with the SAR scene out of a station list provided by the user. The selected GPS stations latitude and longitude coordinates are then projected into the Radar geometry (Range, Azimuth) using the latitude and longitude files, if provided, or the SAR scene 4 corners (provided in the example.rsc/interferogram.out file). The GPS displacements are projected onto the Line-Of-Sight direction using the incidence angle and the heading and compared to the surrounding pixels (default is a 3 pixels wide window). We estimate the orbital parameters by minimizing $||d_{ij}(x,y) - R_{ij}(x,y) - D_{ij}^{GPS}(x,y)||_2$, where, $D_{ij}^{GPS}(x,y)$ is the GPS displacement projected into the LOS at a range x and azimuth y, $d_{ij}(x,y)$ is the phase value averaged over a 3 pixels wide (default) window centered on x and y. Only those GPS stations with colocated coherent InSAR observations are used to estimate the ramps. The orbital function is specified by the option `poly` (default, `poly`= 3) in the function `estramp_gps`.

Two options are available. If the `netramp` option is set to `True` in the Xml file, we estimate each SAR scene orbital parameter at once, ensuring consistency of the orbital parameters in the network sense. Orbital errors are given by,

$$\text{if poly=1,} \quad R_{ij}(x,y) = c_i - c_j, \tag{5.10}$$

$$\text{if poly=3,} \quad R_{ij}(x,y) = (a_i - a_j)\cdot x + (b_i - b_j)\cdot y + c_i - c_j, \text{(default)} \tag{5.11}$$

$$\text{if poly=4,} \quad R_{ij}(x,y) = (e_i - e_j)\cdot xy + (a_i - a_j)\cdot x + (b_i - b_j)\cdot y + c_i - c_j, \tag{5.12}$$

where, a_i, b_i, c_i and e_i are referred to as the orbital parameters for the scene i. Orbital parameters are then combined to produce orbital error maps and correct each interferogram.

If the `netramp` option is set to `False`, orbital errors are estimated independently on each interferogram. In such case, orbital errors are given

by:

$$\text{if poly=3,} \qquad R_{ij}(x,y) = a_{ij} \cdot x + b_{ij} \cdot y + c_{ij}, \tag{5.13}$$

$$\text{if poly=1,} \qquad R_{ij}(x,y) = c_{ij}, \tag{5.14}$$

$$\text{if poly=4,} \qquad R_{ij}(x,y) = e_{ij} \cdot xy + a_{ij} \cdot x + b_{ij} \cdot y + c_{ij}, \tag{5.15}$$

where, a_{ij}, b_{ij}, c_{ij} and d_{ij} are referred to as the orbital parameters for the interferogram ij. We strongly advise the user to set both `gpsramp` and `netramp` options to `True`.

GPS displacements can be computed in three different ways:

- By using the actual raw GPS time series (not recommended).
- Using a smoothed version using cubic splines by setting the `gpspreproc` option to `True` in the **sbas.xml** or **mints.xml** file (recommended).
- By using modeled GPS time series. One can use modelled time series (SOPAC) or only a GPS velocity field.

Using modelled GPS time series is very convenient because it allows to use any functional form. It is also possible to use only the GPS velocities as input to flatten the interferograms. If a crude deformation model is available, it is possible to simulate a dense network of GPS stations and flatten the interferograms.

Implementation

Using the actual GPS time series, smoothed or not, is the default behavior, when the `gpsderamp` code name is set to `True` in the **sbas.xml** or **mints.xml** files. The `netramp` option in the XML file ensures consistency of the orbital parameters in the network sense. The option `gpsvert` will force the software to use vertical GPS displacements. The option `gpspreproc` will smooth the GPS time series before using them (recommended).

The user needs to specify the path to the GPS station list, using the option `stnlist` in the XML file, and what type of list it is, using the option `stntype` in the XML file. The station list type can be

- **False**: This specifies the default station list type, based on the SOPAC format. The station list file is a 14 columns file, as the ones one can download from SOPAC[6]. Only the columns 1, 5, 6 and 8 are used and are station code names in 4 digits, latitude, longitude and starting date of the time series, respectively.

[6] `http://garner.ucsd.edu/pub/timeseries/measures`

- **True**: The station list is a 3 columns Ascii file specifying the station code name (4 digits) and its latitude and longitude coordinates.
- **velocity**: The station list is a 6 columns Ascii file specifying the station code name (4 digits), its latitude and longitude coordinates and the North, East and Up velocities. An example can be found in Appendices. In that case, no GPS station files will be used.

The GPS station files corresponding to the code names in the station file list need to be in the directory specified by the option `gpspath` in the XML file. In the SOPAC standard, each station file name has to be the 4 digits station code followed by `CleanFlt.neu` (ex: `ctmsCleanFlt.neu` for the station `ctms`). Each file is an ASCII file starting by a header, describing the modeled time series, followed by 9 columns, specifying the date (floating point), the year (integer), the day of the year, North displacement, East displacement, Up displacement, North uncertainty, East uncertainty and Up Uncertainty. An example can be found in the Appendices and in the example directory.

5.5 Checklist

1. Check the outputs from the previous step.
2. Gather GPS data in a directory and create a station list file.
3. Copy the **ProcessStack.py** script to your working directory.
4. Run: `python ProcessStack.py [Options]`
5. Weather model data will be automatically downloaded as needed.
6. Check the new HDF5 file and the newly created PNG previews.

Chapter 6

Time-series: SBAS

Small Baseline Subset-like Time Series analysis are among the most common strategies to describe the ground displacements from a pile of interferograms. The name Small Baseline Subset (hereafter SBAS) was primarily chosen by Berardino et al. [2002], but now represents a wide range of methods [e.g, Usai, 2003, Schmidt and Bürgmann, 2003, Cavalié et al., 2007, Lopez-Quiroz et al., 2009]. We have included three implementations of such algorithms in GIAnT - SBAS, N-SBAS and TimeFun. We also provide a way to estimate uncertainties in the estimated time-series products using a cross-validation based approach.

6.1 Inputs

The input files are outputs from **ProcessStack.py** or **PrepIgramStack.py**, including:

- The HDF5 file from **ProcessStack.py** (default is `Stack/PROC-STACK.h5`) or **PrepIgramStack.py** (default is `Stack/RAW-STACK.h5`).
- The XML file containing the informations about the dataset (typically, **data.xml**).
- The XML file containing the informations about the processing strategies (typically, **sbas.xml**).

6.2 Outputs

The output dataset is organized in a single HDF5 file (default is `Stack/LS-PARAMS.h5` for the SBAS chain, `Stack/NSBAS-PARAMS.h5` for the NSBAS chain and `Stack/TIME-FUN.h5` for the time function inversion).

6.3 The SBAS method

6.3.1 Inversion Strategy

The SBAS method is implemented in the scripts **SBASInvert.py** located in the directory `GIAnT/SCR`. This script uses the informations enclosed in the **sbas.xml** and **data.xml** files and the datasets in the HDF5 input file from either **PrepIgramStack.py** or **ProcessStack.py**.

In the traditional SBAS approach, the set of interferometric phase observations writes as a linear combination of individual SAR scene phase values for each pixel independently:

$$d = \mathbf{G}m \iff \Phi_{ij} = \sum_{n=i}^{j-1} \delta\varphi_n, \tag{6.1}$$

where Φ_{ij} is the pixel phase of the interferogram combining acquisition i and j (i.e. in the data vector d) and $\delta\varphi_n$ is the pixel phase increment between acquisition time n and $n+1$ (.i.e in the model vector m). Here, we select pixels where the dataset is complete (i.e. all interferograms and all acquisition dates are available). This way, we form the linear operator $\mathbf{G}$ once and invert it only once using a least squares scheme.
To run this script, type:

```
>> python SBASInvert.py -h -i FNAME -o ONAME -d DXML -p PXML
```

The command line options are:

- **-h**: Ask for help
- **-i FNAME**: FNAME input HDF5 file. Default is `PROC-STACK.h5`.
- **-o ONAME**: ONAME output HDF5 file. Default is `LS-PARAMS.h5`.
- **-d DXML**: DXML data XML file. Default is **data.xml**.
- **-p PXML**: PXML parameter XML file. Default is **sbas.xml**.

6.3.2 Uncertainties estimation

The script **SBASxval.py** provides an uncertainty estimate for each pixel and epoch. For each pixel, a Jacknife test is performed using subsets generated on the basis of SAR acquisitions. For all SAR acquisitions, we form and invert for the linear system $d_n = \mathbf{G}_n m_n$ corresponding to the dataset without the nth acquisition date. For a dataset with M interferograms, combining N acquisitions, we invert for N linear systems. The standard deviation of the m_n vectors represents the uncertainty. Note that the master SAR acquisition is included in all the subsets and is used as the temporal reference.
To run this script, type:

```
>> python SBASxval.py -h -i FNAME -o ONAME -d DXML -p PXML
```

The command line options are:

- **-h**: Ask for help
- **-i FNAME**: FNAME input HDF5 file. Default is `PROC-STACK.h5`.
- **-o ONAME**: ONAME output HDF5 file. Default is `LS-PARAMS.h5`.
- **-d DXML**: DXML data XML file. Default is **data.xml**.
- **-p PXML**: PXML parameter XML file. Default is **sbas.xml**.

6.3.3 Outputs

Outputs are stored in a HDF5 file. Default is `Stack/LS-PARAMS.h5` for **SBASInvert.py** and `Stack/LS-xval.py` for **SBASxval.py**. The variables are:

- `cmask`: Mask map of the pixels.
- `dates`: Dates of acquisitions.
- `mName`: Name of each model parameter function.
- `masterind`: Index of the master acquisition date.
- `parms`: Output parameter vectors of each pixels inversion.
- `rawts`: Raw time-series for each pixel.
- `recons`: Filtered Time Series for each pixel.

- `regF`: Regularization indicator for model parameters.
- `tims`: Time vector in years, with respect to the master date.
- `error`: Error estimation (only with **SBASxval.py**).

For visualization, please refer to section 8.

6.3.4 Checklist

1. Copy the **SBASInvert.py** script to your working directory.
2. Run: `python SBASInvert.py [Options]`.
3. Wait a minute or two.
4. Copy the **plotts.py** script to your working directory.
5. Check the results by running: `python plotts.py [Options]`. See section 8.
6. If you are happy, copy the **SBASxval.py** script to your working directory.
7. Run: `python SBASxval.py [Options]`

6.4 The NSBAS method

The NSBAS method is implemented in the scripts **NSBASInvert.py** and **NSBASxval.py** located in the `GIAnT/SCR` directory. These scripts use the parameters in **sbas.xml** and **data.xml** files and the datasets in the HDF5 input file from either **PrepIgramStack.py** or **ProcessStack.py**. Extended descriptions of the inversion can be found in Lopez-Quiroz et al. [2009], Doin et al. [2011] and Jolivet et al. [2012].

6.4.1 Inversion strategy

This script **NSBASInvert.py** estimates the LOS phase change of each pixel independently using a linear system built with an ensemble Γ of interferograms and a set of a priori constraints combining N acquisition dates:

$$d = \mathbf{G}m \iff \begin{cases} \forall (i,j) \in \Gamma & \Phi_{ij} = \sum_{n=i}^{j-1} \delta\varphi_n \\ \\ \forall k \in [2,N] & 0 = \sum_{n=1}^{k-1} \delta\varphi_n - f(\Delta t_k) + e\mathrm{B}_{perp}^{k} \end{cases} \tag{6.2}$$

where, Φ_{ij} is the pixel phase value for the interferogram combining acquisition i and j (.i.e in the data vector d), $\delta\varphi_n$ is the phase increment between acquisition n and $n+1$, $\Delta t_k = t_k - t_0$, e is a Digital Elevation Model error estimation, B^k_{perp} is the perpendicular baseline between satellite paths at acquisition 1 and k. f is a parametric representation of the temporal form of the deformation. This function needs to be specified in the `userfn.py` file, using the `NSBASdict` function. By default, it is assumed to be of the form:

$$f(t) = at^2 + vt + c, \tag{6.3}$$

where a is the pixel acceleration, v is the pixel velocity and c is a constant. The resulting linear operator $\mathbf{G}$ can be written,

$$\left(\begin{array}{cccccc|cc} & & & & & & 0 & 0 \\ & & & D & & & \vdots & \vdots \\ & & & & & & 0 & 0 \\ \hline 1 & 0 & & & \cdots & 0 & -f(\Delta t_1) & -B^1_{perp} \\ 1 & 1 & & & & 0 & -f(\Delta t_2) & -B^2_{perp} \\ 1 & 1 & 1 & & & 0 & -f(\Delta t_3) & -B^3_{perp} \\ \vdots & & & & & \vdots & \vdots & \vdots \\ 1 & 1 & 1 & \cdots & 1 & 0 & & \\ 1 & 1 & 1 & 1 & \cdots & 1 & -f(\Delta t_N) & -B^N_{perp} \end{array}\right), \tag{6.4}$$

where D is the design matrix relating acquisitions to interferograms through equation 6.2.

The function f is used as a regularization function. Its contribution in the linear operator $\mathbf{G}$ is weighted by a parameter γ, small enough so that, if the SBAS network is complete (i.e. no link between acquisitions is missing), the bottom part of $\mathbf{G}$ does not influence the inversion and is a fit to the data. If the SBAS network is incomplete and disconnected subsets arise, then the functional form links these subsets. By default, we set the γ parameter to 1e-4. This value can be modified using the command line option `-gamma`.

Practically, the **NSBASInvert.py** script reads the HDF5 file, creates the full linear operator $\mathbf{G}$. Then, pixel by pixel, it selects the lines and columns of $\mathbf{G}$ corresponding to this particular pixel's interferometric network and invert the system using this new operator. Each model parameters are stored in the output HDF5 file, together with the phase filtered and un-

filtered evolution. This script is parallelized and multiple threads can be used on a single machine.

To run this script, type:

```
>> python NSBASInvert.py -h -i FNAME -o ONAME -d DXML -p PXML
                         -nproc NPROC -gamma GAMMA
```

The command line options are:

- **-h**: Ask for help.
- **-f FNAME**: Name the of the input HDF5 file. Default is `Stack/PROC-STACK.h5`.
- **-o ONAME**: Name of the output HDF5 file. Default is `Stack/NSBAS-PARAMS.h5`.
- **-d DXML**: DXML is the data Xml file. Default is **data.xml**.
- **-p PXML**: PXML is the parameter Xml file. Default is **sbas.xml**.
- **-nproc NPROC**: Number of processes. Default is 1.
- **-gamma GAMMA**: Weighting parameter. Default is 1e-4.

6.4.2 Traditional stacking [1] as special case

The simplest method to analyze a pile of interferograms is to estimate the Line-of-Sight velocities. Even though such an analysis does not take into account temporal variations in deformation rates compared to robust time-series methods, it is still a good way to quickly look at one's dataset. The traditional velocity estimation by stacking is just a special case of NSBAS inverstion that uses a linear function in time to tie observations between disconnected interferogram clusters. The velocity map is stored as one of the estimated model parameters in the output HDF5 file.

6.4.3 Uncertainties estimation

The script **NSBASxval.py** has not been written for now, but should be available soon.

[1] Velocity estimates

6.4.4 Outputs

Outputs are stored in a HDF5 file. Default is `Stack/NSBAS-PARAMS.h5` for **NSBASInvert.py**. The variables are:

- `cmask`: Mask map of the pixels.
- `dates`: Dates of acquisitions.
- `mName`: Name of each model parameter function.
- `gamma`: Weighting parameter value.
- `ifgcnt`: Number of interferogram used for each pixel.
- `masterind`: Index of the master acquisition date.
- `parms`: Output parameter vectors of each pixels inversion.
- `recons`: Reconstructed filtered Time Series of each pixels.
- `rawts`: Reconstructed un-filtered Time Series.
- `regF`: Regularization indicator for model parameters.
- `tims`: Time vector in years, with respect to the master date.

For visualization, please refer to section 8

6.4.5 Checklist

1. Copy the **NSBASInvert.py** script to your working directory.
2. Modify the `userfn.py` function, if you want a constraint function different from the default one.
3. Run: `python NSBASInvert.py [Options]`.
4. Copy the **plotts.py** script to your working directory.
5. Check the results by running: `python plotts.py [Options]`. See section 8.

6.5 The TimeFun method

The TimeFun method is implemented in the **TimefnInvert.py** script, located in the `GIAnT/SCR` directory. These scripts use the information enclosed in the **sbas.xml** and **data.xml** files and the datasets in the Hdf5 files from either **PrepIgramStack.py** or **ProcessStack.py**. This inversion method is extensively described in Hetland et al. [2011], where it is applied in the wavelet domain.

6.5.1 Inversion strategy

The TimeFun method is an implementation of the temporal inversion scheme developed originally for MInTS [Hetland et al., 2011] directly in the data domain. This method allows one to describe each pixel's phase evolution using a dictionary of user defined functions. For each pixel (m, n), we invert the following linear system,

$$d^{mn} = \mathbf{G}m^{mn} \iff \forall(i,j) \in \Gamma \Phi_{ij}^{mn} = \sum \alpha_k^{mn}(f^k(t_i) - f^k(t_j)) + e^{mn}B_{perp}^{ij}, \tag{6.5}$$

where Γ is the set of all interferograms ij combining the SAR acquisitions with indices i and j, t_i and t_j are the SAR acquisition times, Φ_{ij}^{mn} is the pixel's phase value of interferogram ij (i.e. in the d^{mn} vector). f^k are a set of user defined functions chosen in the provided library that includes seasonal oscillations, polynomial forms, spline functions, integrated spline functions, step functions etc, α_k^{mn} are the corresponding coefficients (i.e. in the vector m^{mn}). B_{perp}^{ij} is the perpendicular baseline of the interferogram ij and e^{mn} is the Digital Elevation Model error term. You can turn on the estimation of e^{mn} using the `demerr` option in the XML file. We build the linear operator $\mathbf{G}$ once and only for pixels that have valid phase observations in all the interferograms.

To set up your functional form, you need to modify the file `userfn.py`. Unless you already did this before, copy this file from `GIAnT/SCR` to your working directory and modify the function `timedict` using the possible keywords (see Appendices, section B.1.1). This file needs to be provided as no default behaviour is assumed by the script.

Two options are possible to invert this linear system and need to be set in the **sbas.xml** file (see section 4.4.2):

- if `regu` is `False`, then, for each pixel mn, we minimize the cost function, F_c^{mn} given by,

$$F_c^{mn} = ||\mathbf{G}m^{mn} - d^{mn}||_2^2. \tag{6.6}$$

The resulting model is the classic non-regularized least-square solution.

- if `regu` is `True`, then, for each pixel mn, we minimize the cost function, F_c^{mn} given by,

$$F_c^{mn} = ||\mathbf{G}m^{mn} - d^{mn}||_2^2 + \lambda^2||Hm^{mn}||_2^2, \tag{6.7}$$

where, H is the laplacian operator. In that case, the damping parameter λ is chosen using a generalized singular value decomposition approach. The regularization is only applied on interpolating functions such as the spline functions and the integrated spline functions, and not on the other functions.

To run this script, type:

```
>> python TimefnInvert.py -h -i FNAME -o ONAME -d DXML -p PXML
                              -nproc NPROC -u USER
```

The command line options are:

- **-h**: Ask for help.
- **-i FNAME**: Name of the input Hdf5 file. Default is `Stack/PROC-STACK.py`.
- **-o ONAME**: Name of the output Hdf5 file. Default is `Stack/TS-PARAMS.py`.
- **-d DXML**: DXML is the data Xml file. Default is **data.xml**.
- **-p PXML**: PXML is the parameter Xml file. Default is **sbas.xml**.
- **-nproc NPROC**: Number of processes. Default is 1.
- **-u USER**: The python script with the user defined time dictionary function. Default: userfn.py.

6.5.2 Uncertainties estimation

The script **Timefnxval.py** provides an estimation of the uncertainties on the model parameters, using a Jacknife approach and can be used the same way as **TimefnInvert.py**.

6.5.3 Outputs

The output datasets are stored in a HDF5 file (default is `Stack/TS-PARAMS.h5`). The datasets are:

- `parms`: Inverted parameters.
- `recons`: Reconstructed phase evolution.
- `mName`: Name of the functions specified in `userfn.py`.
- `regF`: Vector indicating wether a function is regularized or not.
- `tims`: Time vector.
- `dates`: Acquisition dates.
- `cmask`: Mask map of the pixels.
- `masterind`: Index of the master SAR acquisition.

For visualization, please refer to section 8

6.5.4 Checklist

1. Copy the script **TimefnInvert.py** to your working directory.
2. Copy (if not done already) and modify the file `userfn.py`.
3. Run: `python TimefnInvert.py [Options]`.
4. Check Results using plotts.py (see section 8).

6.6 Important Note

We have described three different implementations of SBAS-type algorithms in this manual. One of the key strengths of GIAnT is its modularity. It should be fairly simple for the user to incorporate any features from the MInTS processing chain into their SBAS-type processing strategy A simple example would be to explore the use of Covariance matrices and the shape smoothed regularization in Timefun similar to MInTS.

Chapter 7

Time-series: MInTS

Multiscale InSAR Time-Series (MInTS) [Hetland et al., 2011] was originally developed at Caltech and is different from traditional SBAS approaches in two significant ways.

1. The interferometric phase data is transformed into wavelet domain before temporal inversion.
2. A dictionary of user-defined functions is used to describe the temporal evolution of surface deformation.

The original MInTS software was developed in a MATLAB framework and is available for download at `https://secure.earth.lsa.umich.edu/groups/lithosphere/wiki/eb455/MInTS.html`. We have reimplemented the entire package in Python for speed and efficiency. Some of the important components of GIAnT like the Meyer wavelet library and the Tikhonov solver were written primarily for implementing the various MInTS algorithms in Python.

7.1 The MInTS Algorithm

The MInTS processing chain has been extensively described in Hetland et al. [2011]. The processing steps include wavelet transform of the interferograms, parametrized inversion of the wavelet coefficients and inverse wavelet transform of the coefficients. These steps are implemented in the scripts called **DatatoWavelet.py**, **InvertWaveletCoeffs.py** and **WavelettoData.py**. The MInTS processing chain typically follows the atmospheric removal and the flattening of the interferograms, using **ProcessStack.py**.

7.2 Forward Wavelet Transform

The forward wavelet transform process is done using the **DatatoWavelet.py** script, located in the `GIAnT/SCR` directory. This step includes:

1. **Inpainting** - Small decorrelated holes in the interferograms are filled in with an inpainting algorithm. We use a Python version of the inpaint_nans utility [D'Errico, 2006].

2. **Mirroring** - Fast Wavelet Transform (FWT) algorithms are set up to work on matrices of dyadic lengths. We mirror our inpainted images to dyadic lengths before transforming the data. The bounds of the original data in the mirrored array are also saved for future use. The option `minpad` in the **mints.xml** file ensures a minimum fraction of the interferogram width and length will be used for mirroring (default is 0.1).

3. **Forward Wavelet Transform** - We apply the FWT to the mirrored data. We provide support for Meyer wavelets through our own Python library derived from the Wavelab package [Buckheit and Donoho, 1995] and for other wavelets through the pywt package [Wasilewski, 2012]. To use the Meyer wavelets, set the option `wvlt` to `meyer` in the **mints.xml** file.

4. **Reliability Measure** - We also compute the reliability measure of wavelet coefficients by convolving the absolute value of the impulse response with a binary mask representing original and interpolated data.

This script has been parallelized using Python's multiprocessing module and the results of this processing step are stored in **Stack/WAVELET.h5**. To run **DatatoWavelet.py**, type:

```
>> python DatatoWavelet.py  -h -i INAME -o ONAME -nchunk NCHUNK
                            -nproc NPROC -d DXML -p PXML
```

The command line options are:

- **-h**: Ask for help.
- **-i INAME**: input Hdf5 file. Default is defined by the parameters in the parameter Xml file (i.e. if no pre-processing is asked, default is `Stack/RAW-STACK.h5`, otherwise, it is `Stack/PROC-STACK.h5`).
- **-o ONAME**: output Hdf5 file. Default is `Stack/WAVELET.h5`.

- **-d DXML**: data XML file. Default is **data.xml**.
- **-p PXML**: parameter Xml file. Default is **mints.xml**.
- **-nchunk NCHUNK**: Number of interferograms processed in parallel. Default is 40.
- **-nproc NPROC**: Number of processes to operate on a chunk. Default is 1.

The outputs datasets are stored in a HDF5 file (default is `Stack/WAVELET.h5`). The datasets are:

- `Jmat`: Matrix linking interferograms to the acquisition dates, made of 0, 1 and -1 (also called connectivity matrix).
- `bperp`: Vector of the perpendicular baseline values.
- `cmask`: Mask map of the pixels.
- `dates`: Dates of acquisition.
- `offset`: Bounds of the mirrored array.
- `tims`: Vector of time of acquisition with respect to the master.
- `wvlt`: Stack of wavelets from the interferograms.
- `wts`: Stack of the Wavelet weights.

7.3 Time-series inversion of the wavelet coefficients

7.3.1 Inversion strategy

The time-series inversion of the wavelet coefficients is done using the script **InvertWaveletCoeffs.py** or **InvertWaveletCoeffs_folds.py**, located in the `GIAnT/SCR` directory. The inversion scheme is similar to the one used in the TimeFun method (Section 6.5.1).

$$\begin{aligned} d^{mn} &= \mathbf{G}m^{mn} \iff \forall (i,j) \in \Gamma \\ W_{ij}^{mn} &= \sum \alpha_k^{mn}(f^k(t_i) - f^k(t_j)) + e^{mn}B_{perp}^{ij} \end{aligned} \tag{7.1}$$

where W_{ij}^{mn} refers to the particular wavelet coefficient with index mn in interferogram ij. Once again the dictionary of temporal functions is passed

to our inversion script using the **userfn.py**. If the user decides to use a non-parametric inversion scheme using splines or integrated splines, the solutions are regularized as described in Appendix E. **InvertWavelet-Coeffs_folds.py** represents our optimized implementation of the original MInTS, using a k-fold cross validation approach to chose the damping parameter.

To run the inversion, type:

```
>> python InvertWaveletCoeffs.py -h -i INAME -o ONAME -d DXML -p PXML
                                  -nproc NPROC
```

The command line arguments are:

- **-h**: Ask for help.
- **-i INAME**: input Hdf5 file. Default is `Stack/WAVELET.h5`.
- **-o ONAME**: output Hdf5 file. Default is `Stack/WAVELET-INV.h5`.
- **-d DXML**: data XML file. Default is **data.xml**.
- **-p PXML**: parameter Xml file. Default is **mints.xml**.
- **-nproc NPROC**: Number of processes. Default is 1.

The outputs datasets are stored in a Hdf5 file (default is `Stack/WAVELET-INV.h5`). The datasets are:

- `Jmat`: Matrix linking interferograms to the acquisition dates, made of 0, 1 and -1 (also called connectivity matrix).
- `bperp`: Vector of the perpendicular baseline values.
- `cmask`: Mask map of the pixels.
- `dates`: Dates of acquisition.
- `model`: Description of the function used in the inversion.
- `offset`: Bounds of the mirrored array.
- `tims`: Vector of time of acquisition with respect to the master.
- `wvlt`: Stack of wavelets from the interferograms.

7.3.2 Uncertainties estimation

The script **InvertWaveletCoeffs_xval.py** provides an estimation of the uncertainties on the model parameters using the generalized singular value decomposition approach and may be used the same way as **InvertWavelet-Coeffs.py**.

7.4 Inverse Wavelet Transform

The wavelet coefficients estimated in the previous step are transformed into model parameter space using the Inverse Wavelet Transform (IWT). This step is implemented in the **WavelettoData.py** script, located in the `GIAnT/SCR` directory. The image is cropped back to dimensions of the original data set and the deformation time-series is then recreated by putting together the temporal functions and the estimated model parameters. The results are stored in **Stack/WS-PARAMS.h5**.To run this step, type:

```
>> python WavelettoData.py -h -i INAME -o ONAME -d DXML -p PXML
                  -nchunk NCHUNK -nproc NPROC -u USER
```

The command line arguments are:

- **-h**: Ask for help.
- **-i INAME**: input Hdf5 file. Default is `Stack/WAVELET-INV.h5`.
- **-o ONAME**: output Hdf5 file. Default is `Stack/WS-PARAMS.h5`.
- **-d DXML**: data XML file. Default is **data.xml**.
- **-p PXML**: parameter XML file. Default is **mints.xml**.
- **-nchunk NCHUNK**: Number of interferograms processed in parallel. Default is 40.
- **-nproc NPROC**: Number of processes to operate on a chunk. Default is 1.
- **-u USER**: Python script with the user defined python function. Default is userfn.py .

The outputs datasets are stored in a HDF5 file (default is `Stack/WS-PARAMS.h5`). The datasets are:

- `Jmat`: Matrix linking interferograms to the acquisition dates, made of 0, 1 and -1 (also called connectivity matrix).
- `cmask`: Mask map of the pixels.
- `dates`: Dates of acquisition.
- `masterind`: Index of the master date.
- `model`: Model parameters maps.
- `modelstr`: Model description.
- `recons`: Reconstructed phase at each date of acquisition.
- `tims`: Vector of time of acquisition with respect to the master.

7.5 Note

One of the strengths of GIAnT is it's modularity. We currently provide the original implementation of MInTS with the GIAnT. However, it should be trivial for the users to reuse modules from the SBAS-type algorithms and apply them to the wavelet coefficients directly.

7.6 Checklist

1. Convert interferograms to the wavelet domain: `python DatatoWavelet.py [Options]`
2. Check the Hdf5 file produced.
3. Copy (if you have not done so before) the `userfn.py` file in your working directory, and modify the MInTS dictionnary of functions.
4. Run `python InvertWaveletCoeffs.py [Options]`.
5. Check the Hdf5 file produced.
6. Run `python WavelettoData.py [Options]`.
7. Check the results using the script `plotts.py`.
8. Run `python InvertWaveletCoeffs_xval.py` to get the uncertainties.
9. Run `python WavelettoData.py -f WAVELET-INV-xval.h5`.

Chapter 8

Visualization and Geocoding

8.1 Interactive visualization

We provide a visualization tool, called **plotts.py**, located in `GIAnT/SCR`. This tool can be used with any time series output from GIAnT. You can run **plotts.py**, typing:

```
>> python plotts.py -h -e -f FNAME -i TIND -m MULT -y YINF YSUP
                    -ms MSIZE -mask MASKFILE MASKXML -raw
                    -model -zf
```

The command line options are:

- **-h**: Ask for help
- **-f FNAME**: FNAME input HDF5 file with time-series estimates. Default is `Stack/LS-PARAMS.h5`.
- **-i TIND**: index of the slice to display.
- **-m MULT**: multiplicative factor. Default is 0.1 (i.e. results in cm).
- **-y YINF YSUP**: the lower and upper colorbar plot limits. Default is -25 25.
- **-ms MSIZE**: Marker size on the phase evolution plot. Reduce if error bars are too small. Default is 5.
- **-mask MASKFILE MASKXML**: MASKFILE is a binary file used for masking output data, if needed. MASKXML is the Xml file that contains the width and length of the binary file. Default is no mask.

- **-raw**: Flag to display the filtered and un-filtered time series of a pixel (Only for NSBAS outputs).
- **-model**: Plot the modeled phase value, along with the phase change (works only with NSBAS,TimeFun and MInTS) .
- **-zf**: Change the reference time for plotting.
- **-e**: Plot the errorbars if available (works with Xval scripts).

8.2 Movies

We include a simple python script **G**IANT/SCR/make_movie.py to build a quick movie of your estimated time-series in radar coordinates. This script can be used as a template in combination with the geocoding library to make movies in geocoded domain as well. You can generate movies of your time-series using

```
>> python make_movie.py -h -i FNAME -o ONAME -nslice NSLICE
                        -y YINF YSUP -win GWIN -model
                        -pix I0 J0 -fps FPS -geo DXML
```

The command line options are:

- **-h**: Ask for help
- **-i FNAME**: FNAME input HDF5 file with time-series estimates. Default is `Stack/LS-PARAMS.h5`.
- **-o ONAME**: output movie name. Default: movie.mp4 .
- **-nslice NSLICE**: Number of time-slices to divide your total time span into. Default: 100.
- **-y YINF YSUP**: the lower and upper colorbar plot limits. Default is -25 25.
- **-win GWIN**: Width of the Gaussian window in years used for interpolation. Default: 0.33.
- **-pix I0 J0**: (Azimuth,Range) coordinates of pixel in radar coordinates, whose time-series will also be plotted.
- **-model**: If you use a parameteric inversion, use the model to interpolate rather than the reconstructed time-series. Default: False

- **-fps**: Frames per second for the movie. Default: 10.
- **-geo DXML**: The data.xml file. If provided, the movie will be generated in geo-coded domain.

8.3 KML

The estimated time-series can also be spit out as a KML file with a time-slider for immediate visualization in Google Earth. The script is similar to the one that generates movies. The code does include system calls to **ImageMagick's convert** command for making parts of the image transparent and **zip** command to generate a KMZ file from the generated KML and PNG files. A colorbar is also automatically generated as an overlay.

```
>> python make_kml.py -h -i FNAME -x XNAME -o ONAME
                      -nslice NSLICE -y YINF YSUP
                      -win GWIN -model -dir DIRI -trans
```

The command line options are:

- **-h**: Ask for help
- **-i FNAME**: FNAME input HDF5 file with time-series estimates. Default is `Stack/LS-PARAMS.h5`.
- **-o ONAME**: output movie name. Default: movie.mp4 .
- **-nslice NSLICE**: Number of time-slices to divide your total time span into. Default: 100.
- **-y YINF YSUP**: the lower and upper colorbar plot limits. Default is -25 25.
- **-win GWIN**: Width of the Gaussian window in years used for interpolation. Default: 0.33.
- **-model**: If you use a parameteric inversion, use the model to interpolate rather than the reconstructed time-series. Default: False
- **-x DXML**: The data.xml file. This is needed as the file includes information about the lat/lon files.
- **-trans**: The undefined data in the images (NaNs) are made transparent. Default: False

8.4 Geocoding

GIAnT includes geocoding library routines in **G**IAnT/geocode directory. GIAnT uses the pyresample library to transform data to and from radar domain and geocoded domain. Currently, PyAPS and our geocoding modules only support the WGS84 format. Extending support to other projections should be relatively simple using pyresample.

An example script to geocode results from our output HDF5 files has been included in **G**IANT/SCR/rdr2geo.py. The users should copy this script and suitably modify it for their applications. Besides flat binary files, the users should also be able to output data to GMT netcdf format and OGR VRT files using the provided library.

Appendix A

I/O Utilities

A.1 Text files

We include a bunch of functions in **tsio.py** to read in data from ASCII files into python arrays and lists.

- **textread(fname,strformat)**
  This is very similar to textread utilities from MATLAB®.

  ```
  [fname,index,bperp] = textread('input.txt','S I K F')

  S - String, I - Integer, F - Float, K - Skip

  The function returns a single list of values that are read
   in form a space/tab delimited text file.
  ```

- **read_rsc(fname)**
  This allows us to read in a ROI_PAC style RSC file into a python dictionary.

  ```
  rdict = read_rsc('example.unw')

  Note that the .rsc extension in the file name is optional.
  Elements of the dictionary can be accessed as
  rdict['WIDTH'], rdict['FILE_LENGTH'] etc.
  ```

- **write_rsc(rdict,fname)**
  Writes the contents of the dictionary to file give by fname. The keys of the dictionary become the headings for the entries of the RSC file.

A.2 Binary files

We include the following functions to read in files from binary files into numpy arrays.

- **load_mmap(fname, nxx, nyy, map, nchannels, channel, datatype, quiet, conv)**
  This allows to memory map data in a binary file to a numpy array. This function can handle BIL, BIP and BSQ data formats. The default values are (map='BSQ', nchannels=1, channel=1, datatype=numpy.float32, conv=False). Mapping the file to a numpy array allows us to access the contents of the file directly like in an array.

```
#To map a simple float file of size 100 x 100
arr = load_mmap(fname, 100, 100)

#To map an RMG file of size 100 x 100 with phase in channel 2
arr = load_mmap(fname, 100, 100, map='BIL',
         nchannels=2, channel=2)
```

- **load_flt(fname, nxx, nyy, datatype, scale, conv)**
  Load a simple flat binary file into memory. Unlike the memory map, all the data is loaded into memory.
- **load_rmg(fname, nxx, nyy, datatype, scale, conv)**
  Load both channels of an RMG file into memory.

A.3 HDF5 Files

We have two simple utilities for reading and writing HDF5 files in **tsio.py**. These should only be used for simple debugging applications and for small datasets. HDF5 file interface through h5py is already fairly simple and we mostly make direct calls to h5py functions to deal with HDF5 files.

- **saveh5(fname,rdict)**
  Save the contents of specified dictionary (rdict) to a given HDF5 file (fname). The keys of the dictionary automatically become dataset names.
- **loadh5(fname)**
  Returns the contents of a HDF5 file (fname) in a dictionary. The names of the datasets becomes the keys in the dictionary.

A.4 GMT netcdf files

We include simple utilities to read data directly from GMT-style netcdf (grd) files. These are used to load data from GMTSAR products.

- **load_grd(fname, var='z')**
  Load a variable (var) from a given GMT-style netcdf file (fname).
- **get_grddims(fname, var='z')**
  Get the dimensions of a variable (var) from a given GMT-style netcdf file (fname).

A.5 XML Files

We use XML files to set processing parameters for our scripts. We include utilities for reading and writing XML files in **tsxml.py**. All XML processing is done through the TSXML class defined in tsxml.py. We use the lxml.eTree package to generate XML files and lxml.objectify to read them.

A.5.1 XML format

All data entries in our XML files are of format.

```
<params>
<width>
<value>500</value>
<type>INT</type>
<help>Width of interferograms.</help>
</width>
</params>
```

By design, we force all XML field entries (other than branch nodes) to have a help string describing the parameter. This has been enforced to ensure that processing parameters are easily understood by users from different backgrounds. Currently, we support INT, FLOAT, BOOL and STR data types.

A.5.2 Creating XML file

```
#Creating XML with params as root node.
g = TSXML('params')
```

```
br = g.addnode(g.root,'params')
g.addsubelement(br,'width',100,'Width of interferograms.')
g.writexml('data.xml')
```

The TSXML class includes utilities to prepare **data.xml**, **sbas.xml** and **mints.xml**. These different XML files are used for processing and are created using the **prepxml.py** utility provided with the scripts. We also provide a method to create a generic XML file using keywords.

A.5.3 Reading XML file

```
#Reading an XML file.
h = tsinsar.TSXML('data.xml',File=True)
wid = h.data.master.width
```

All the data in XML is converted into a structured object that can be directly used in your scripts.

A.6 DEM RSC file for non ROI_PAC data

Here is an example RSC file to be included with the radar simulation or DEM in case, the data was processed using a processor other than ROI_PAC. The dimensions are the most important part of this file. The latitude and longitude values are read in to determine the approximate bounds of the scene for subsetting weather model data.

```
WIDTH     350
FILE_LENGTH 500
LAT_REF1 38.5
LON_REF1 -119.5
LAT_REF2 37.3
LON_REF2 -118.0
LAT_REF3 38.5
LON_REF3 -119.5
LAT_REF4 37.3
LON_REF4 -118.0
AZIMUTH_PIXEL_SIZE 180.000000
RANGE_PIXEL_SIZE 63.300000
```

A.7 GPS Input Files

A.7.1 Option 1: Velocity type station list

The station locations and average velocities are provided in a single file.

```
a001     11.80000     42.80000      0.00604      0.01106     -0.00000
a002     12.00000     42.80000      0.00591      0.01106     -0.00000
a003     12.00000     43.00000      0.00592      0.01119      0.00000
a004     12.00000     43.20000      0.00592      0.01131      0.00000
....
```

A.7.2 Option 2: Station-wise time series

The coordinates of the GPS station can be provided in two different ways:

Option a: Classic Station List

```
7odm  34.11640714 -117.09319315
ab01 52.20950520 -174.20475602
ab02 52.97060620 -168.85467007
ab04 63.65686535 -170.56744305
...
```

Option b: SOPAC station list

This data can be retrieved by e-mail from the SOPAC archive.

```
7odm -2407750.9707 -4706536.6674  3557571.4197  34.11640714 -117.09319315  \\
 762.0806 2004.4932 0.0048 0.0059 0.0046 0.0024 0.0043 0.0074
ab01 -3896562.8770  -395471.6423  5017141.8417  52.20950520 -174.20475602   \\
 25.4568 2004.4932 0.0031 0.0019 0.0037 0.0018 0.0019 0.0045
ab02 -3776808.0832  -744083.8296  5068728.1267  52.97060620 -168.85467007  \\
 192.7802 2004.4932 0.0024 0.0014 0.0029 0.0017 0.0014 0.0034
ab04 -2799600.4279  -465105.4035  5692966.4183  63.65686535 -170.56744305   \\
136.5690 2004.4932 0.0025 0.0011 0.0044 0.0015 0.0010 0.0048
....
```

Station File example

The time-series of individual stations must be described in the SOPAC format.

```
#########################################################################
# Refined Model Terms:
#
#                     n component
#     slope 1: -0.0088 +/- 0.0000 m/yr (1999.1932 - 2010.0644)
#    offset 1: -0.0002 +/- 0.0002 m (1999.6178)
#      annual:  0.0012 +/- 0.0001 m; phase: 4.10
# semi-annual:  0.0003 +/- 0.0000 m; phase: 2.84
#
#                     e component
#     slope 1: -0.0153 +/- 0.0000 m/yr (1999.1932 - 2010.0644)
#    offset 1:  0.0013 +/- 0.0002 m (1999.6178)
#      annual:  0.0007 +/- 0.0001 m; phase: 4.51
# semi-annual:  0.0004 +/- 0.0001 m; phase: 1.48
#
#                     u component
#     slope 1:  0.0000 +/- 0.0001 m/yr (1999.1932 - 2010.0644)
#    offset 1: -0.0031 +/- 0.0006 m (1999.6178)
#      annual:  0.0048 +/- 0.0002 m; phase: 3.98
# semi-annual:  0.0008 +/- 0.0001 m; phase: 2.53
#
# ------------------------------------------------------------------
#
#########################################################################
1999.1932 1999 071  0.0486  0.0834 -0.0011  0.0025  0.0020  0.0026
1999.1959 1999 072  0.0488  0.0828 -0.0004  0.0024  0.0019  0.0025
1999.1986 1999 073  0.0484  0.0829  0.0000  0.0024  0.0019  0.0026
1999.2014 1999 074  0.0492  0.0820 -0.0030  0.0025  0.0020  0.0026
1999.2041 1999 075  0.0491  0.0827 -0.0006  0.0026  0.0021  0.0027
1999.2068 1999 076  0.0490  0.0821 -0.0015  0.0024  0.0019  0.0025
1999.2096 1999 077  0.0493  0.0828  0.0006  0.0024  0.0019  0.0026
1999.2123 1999 078  0.0496  0.0835  0.0008  0.0027  0.0021  0.0028
1999.2151 1999 079  0.0497  0.0827  0.0025  0.0026  0.0021  0.0028
1999.2178 1999 080  0.0489  0.0821 -0.0012  0.0025  0.0020  0.0026
...
```

Appendix B

Time-series Utilities

B.1 Temporal characterization

One of the strengths of GIAnT is the freedom for representing the temporal behaviour of surface deformation as a combination of functions from a predefined dictionary, including b-splines and integrated b-splines. We provide a simple framework to call this dictionary of functions and build design matrices. The related functions are included in the file **tsutils.py**. The most relevant function is **tsutils.Timefn(rep,t)**.

B.1.1 Dictionary of functions

We currently provide support for the following functions. It is trivial to customize and add functions to the dictionary.

- **Linear rate**
  Python representation `['LINEAR',[t1,t2,...,tN]]` is equivalent to N rows of design matrix such that

$$f_k(t) = (t - t_k) \tag{B.1}$$

- **Polynomial**
  Python representation `['POLY',[p1,p2,...,pN],[t1,t2,...,tN]]` is equivalent to `sum([p1,..,pN])+N` rows of the design matrix such that

$$f_{i,k}(t) = (t - t_i)^k \quad i \in [0, 1, ..., p_i] \tag{B.2}$$

- **Power**
  Python representation `['POW',[p1,p2,...,pN],[t1,t2,...,tN]]` is

equivalent to `N` rows of the design matrix such that

$$f_k(t) = (t - t_k)^{p_k} \tag{B.3}$$

- **Exponential decay**
  Python representation `['EXP',[t1,t2,...,tN],[tau1,tau2,...,tauN]]` is equivalent to N rows of the design matrix such that

$$f_k(t) = \left[1 - \exp\left(\frac{t - t_k}{\tau_k}\right)\right] \cdot u(t - t_k) \tag{B.4}$$

- **Logarithmic decay**
  Python represetntation `['LOG',[t1,t2,...,tN],[tau1,tau2,...,tauN]]` is equivalent to N rows of the design matrix such that

$$f_k(t) = \log\left(1 + \frac{t - t_k}{\tau_k}\right) \cdot u(t - t_k) \tag{B.5}$$

- **Step function**
  Python representation `['STEP',[t1,t2,...,tN]]` is equivalent to N rows of the design matrix such that

$$f_k(t) = u(t - t_k) \tag{B.6}$$

- **Seasonal**
  Python representation `['SEASONAL',[tau1,tau2,...,tauN]]` is equivalent to 2N rows of the design matrix such that

$$\begin{aligned} f_{2k-1}(t) &= \cos\left(2\pi\frac{t}{\tau_k}\right) \\ f_{2k}(t) &= \sin\left(2\pi\frac{t}{\tau_k}\right) \end{aligned} \tag{B.7}$$

- **B-Splines**
  Python representation `['BSPLINE',[Ord1,...,OrdN],[n1,...,nN]]` is equivalent to `prod([n1,...nN])*len(t)` rows of the design matrix. "Ord_k" represents the order and "n_k" represents the number of equally spaced splines between minimum and maximum values of the time vector.

- **Integrated B-Splines**
  Python representation `['ISPLINE',[Ord1,...,OrdN],[n1,...,nN]]` is equivalent to `prod([n1,...nN])*len(t)` rows of the design matrix. "Ord_k" represents the order and "n_k" represents the number of equally spaced splines between minimum and maximum values of the time vector.

B.1.2 Putting functions together

```
rep = [ ['LINEAR',[0.0,9.5]],

      ['EXP',[4.0,8.0],[1.0,3.0]],

      ['BSPLINE',[3],[16]],

      ['LOG',[2.0,9.0],[1.0,3.0]],

      ['SEASONAL',[0.5,1.0]],

      ['ISPLINE',[3],[16]]]

H,vname,rflag = tsutils.Timefn(rep,t)
```

H represents the design matrix, **vname** is a list with a unique name for each parameter in our temporal model and **rflag** is a vector indicating if the particular parameter needs to be regularized. The rflag vector is automatically used to construct the regularization operator. If multiple families of splines are used with different scales, each family has a unique regularization flag. Thus, the regularization operator automatically takes this into account.

B.1.3 SBAS Formulation

We also use the same Timefn to generate the design matrix for implementing SBAS.

```
H,vname,rflag = Timefn(['SBAS',[masterind]])
```

We allow the users to choose a master scene other than first SAR acquisition for formulation their time-series inversions. The users may need to make minor adjustments to the returned matrix depending on the exact implementation of the inversion scheme. Examples of such adjustments can be found in various SBAS-style scripts distributed with GIAnT.

B.2 Network utilities

We also provide a set of functions to create interferogram network related matrices.

- **ConnMatrix(dates,sensor)**
  Creates the connectivity matrix $[1, -1]$ for the interferogram network using the dates and satellite sensor as inputs.

- **conntoPairmat(Jmat)**
  Returns an edge list of interferograms using the connectivity matrix as input.

- **conntoAdjmat(Jmat)**
  Returns the adjacency matrix using the connectivity matrix as input.

- **adjmattoAdjlist(Amat)**
  Returns the adjacency list using the adjacency matrix as input.

- **simpleCycle(Jmat)**
  Returns a list of all simple cycles using the connectivity matrix as input.

Appendix C

Image utilities

GIAnT also includes a few 2D array manipulation routines, typically used in preparing interferograms before processing.

C.1 MInTS image routines

These are routines used in preprocessing interferograms before wavelet transforms in MInTS.

- **mints.inpaint(matrixwithnans)**
  The routine inpaints nans in the input matrix similar to the inpaint_nans (`http://www.mathworks.com/matlabcentral/fileexchange/4551-inpaintnans`) package developed by John D' Errico. We have only implemented the spring metaphor.
- **mints.Mirrortodyadic(matrix, frac)**
  Mirrors the input matrix to a dyadic length such that a specfied fraction is always mirrored. This is done to reduce edge effects in the wavelet transforms. Mirroring fraction is typically 20%.

C.2 Stack routines

These routines are used for processing stacks in general and are included in **stackutils.py** .

- **Lookdown(matrix,looks,method,varFalse)**
  Multi-looking of interferograms. Method can either be - mean or median. If desired, the variance of multi-looked chips are also returned.

- **estramp(phs,mask,poly)**
  Estimates the ramp polynomial for an unwrapped interferogram using a mask. Poly can be either 1, 3 or 4.

- **deramp(phs,ramppoly)**
  Deramping of interferograms using a polynomail. Poly can be of length 1 (constant), 3 (Planar) or 4 (Product of linear terms).

- **nanmean(x)**
  Returns the mean of an array while taking care of NaNs.

Appendix D

Wavelets

The original implementation of MInTS Hetland et al. [2011] used the Meyer wavelet routines in the Wavelab850 package (`http://www-stat.stanford.edu/~wavelab`) for all wavelet operations. We have rewritten the Meyer wavelet routines in Python and have added new ones for analyzing rectangular datasets. We have also added routines that efficiently compute the impulse response and the reliability score of wavelet coefficients over interpolated holes. All routines related to the Meyer wavelet transforms can be found in **meyer.py**.

We have also included support for different wavelet functions using the pyWavelets package. The interface to **meyer.py** has been replicated for these set of wavelet basis in **wvlt.py**. Though, we prefer to work with Meyer wavelets in our work these other wavelets can be used in the development of future applications.

In our approach, we use wavelets to reduce the effect of spatially correlated noise in the estimated time-series. We explicitly avoid interpreting the information at various spatial scales as different components of deformation/ orbits / atmosphere like Shirzaei and Walter [2011], as these may be dependent on the family of wavelets used for analysis.

D.1 Convention

The original version of MInTS used cells to store matries of wavelet coefficients. We have decided to retain all the wavelet coefficients in a single 2D matrix (same size as original data matrix) for faster access during time-series inversions. This also allows us to use other features of MInTS directly for time-series analysis of InSAR data directly, instead of the wavelet coeffi-

cients if needed. Instead of the cell structure, we provide a lookup function that returns the four corners of the sub-matrix that contains the coefficients at a particular scale and quadrant. We have also reversed the labelling of scales in MInTS to directly relate the scale to the number of wavelet coefficients at any particular scale. Figure D.1 describes the convention used in MInTS to store the wavelet coefficients.

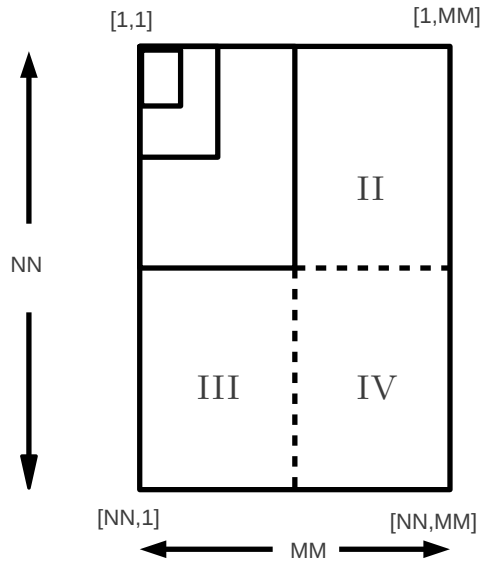

Figure D.1: Wavelet transform convention of an image of size (NN × MM). We always assume that NN ≥ MM in the routines. The smallest scale for analysis is 3 (corresponding to 8 pixels along width) and the highest scale corresponds to $\log_2(\mathrm{MM})-1$ (corresponding to half the width of the image). The quadrants are named according to the convention shown above.

D.2 Routines

The functions in our custom written Meyer wavelet library (meyer.py) are

- **w = meyer.fwt2_meyer(matrix,degree,minscale)**
  2D wavelet transform of rectangular matrix. Scale definition is with

respect to the width of the image. Dyadic lengths assumed. "degree" and "minscale" always set to 3, for all the functions.

- **mat = meyer.iwt2_meyer(matrix,degree,minscale)**
  2D inverse wavelet transform of rectangular matrix. Scale definition is with respect to the width of the image. Dyadic lengths assumed. "degree" and "minscale" always set to 3, for all the functions.

- **ii,jj = meyer.get_corners(matrix.shape,scale,quadrant)**
  Returns the minimum and maximum values of rows and columns of the sub-matrix corresponding to the specified scale and quadrant, from a given wavelet coefficient matrix. This mechanism is the alternative to the cell structure used in the original MInTS software.

- **meyer.impulse_resp(matrix.shape,fname)**
  Writes the impulse response for 2D wavelet transform for a matrix of given shape to a specified HDF5 file. This is an important change to MInTS and now allows us to apply MInTS to very large matrices with ease. The impulse response for a matrix of given size (dyadic lengths) must be computed and stored before the analysis of the wavelet coefficients.

- **wt = meyer.CoeffWeight(mask,responsefname)**
  Computes the reliability of wavelet coefficients using the mask of real and interpolated data, and the HDF5 file containing the appropriate impulse response as inputs.

D.3 Other wavelets

The functions in our generalized wavelet library (wvlt.py) are designed to be compatible with our original Meyer wavelet library. The corresponding functions are

- **w = wvlt.fwt2(matrix,wvlt='db12')**
- **mat = wvlt.iwt2(matrix,wvlt='db12')**
- **ii,jj = wvlt.get_corners(matrix.shape,scale,quadrant)**
- **wvlt.impulse_resp(matrix.shape,fname,wvlt='db12')**
- **wt = wvlt.CoeffWeight(mask,responsefname,wvlt='db12')**

Appendix E

Solvers

Various inversion algorithms are used to various stages of processing in GIAnT. We have included a set of customized solvers in the solver directory.

E.1 Least squares

Numpy and Scipy have inbuilt optimized least squares solvers. We use these solvers with the default conditional parameter of **rcond**$= 1.0e-8$ for stability.

E.2 Regularized L_2 norm

We use Tikhonov regularization for inversions in our MInTS (Chapter 7) implementation and for TimefnInvert (Chapter 6) . Our implementation of Tikhonov regularization is included in **tikh.py** in the solver directory. We use the class TIKH to setup and solve our problems. We set up the regularized minimization formulation as

$$\underset{m}{\text{argmin}} \;\; ||G \cdot m - d||^2 + \lambda||H \cdot m||^2 \tag{E.1}$$

where G is the design matrix, m represents model parameters, H is the smoothing or damping matrix and d represents the set of observations. The regularization parameter λ can be chosen in multiple ways:

1. Generalized Cross Validation (GCV)

2. Curvature of the L-curve

3. Quasi optimality condition

4. K-fold cross validation

Our implementation of the first three methods is based on the regutools toolbox Hansen [2007]. We have adopted LAPACK's dggsvd routine to compute the generalized SVD. Our generalized SVD (gsvd module) returns a factorization that is different from the one returned by cgsvd from regutools. We have suitably modified our solver functions to account for this. As suggested on the regutools webpage, we also implemented a pre-processor for the regularization operator (H) using a rank revealing QR decomposition from UTV tools Fierro et al. [1999]. All the four algorithms can be ranked according to performance as follows:

Table E.1: Performance of various regularization parameter selection algorithms.

Method	Speed	Smoothness of solution
GCV	Fast	Roughest
L-curve	Fast	Rough
Quasi optimality	Fastest	Smoothest
K-folds	Slow	Moderately smooth

E.3 Iteratively reweighted least squares

We also included an implementation of the IRLS solver in the script **iterL1.py**. We use IRLS for empirical correction of topography-correlated atmosphere [Lin et al., 2010b].

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