Interferometry Tutorial

Displacement measurement

SARscape Version 5.7.0

August 2023

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1. Introduction

The main goal of this tutorial is to give a basic description of the SARscape Differential Interferometric Synthetic Aperture Radar (DInSAR) processing chain to obtain a **displacement map** from a pair of SAR images.

Interferometric synthetic aperture radar exploits the phase difference between two complex radar SAR observations taken from slightly different sensor positions and extracts information about the earth's surface. A SAR signal contains amplitude and phase information. The amplitude is the strength of the radar response and the phase is the fraction of one complete sine wave cycle (a single SAR wavelength). The phase of the SAR image is determined primarily by the distance between the satellite antenna and the ground targets. Interferometry consists of combining the phase of two SAR images (Reference and Secondary images), by cross-multiplying, pixel by pixel, the first SAR image with the complex conjugate of the second. The result is a new complex number whose module is the product of the module of the two input SAR images, and whose phase is the difference between the phases of the two input images. The two input images must be aligned (coregistered).

The interferometric phase is the contribution of 4 components: the topographic component, the phase noise component, the displacement component, and the atmosphere component:

$$\varphi_{Int} = \varphi_{Topography} + \varphi_{Change} + \varphi_{Movement} + \varphi_{Atmosphere}$$

The terms φ_{Change} and $\varphi_{Atmosphere}$ are gathered in φ_{Noise} :

$$\phi_{Int} = \phi_{Topography} + \phi_{Movement} + \phi_{Noise}$$

There are two unknowns (φ_{Topo} and $\varphi_{Movement}$) and one measure (φ_{Int}); it is therefore necessary to make the assumption that the measure is totally topography or movement.

DEM generation:

$$\phi_{Int} = \phi_{Topography} + \phi_{Noise}$$

Displacement generation:

$$\phi_{Int} = \phi_{Movement} + \phi_{Noise}$$

For displacement measurement purposes it is necessary to make the assumption that the interferometric measure is totally relevant to displacement, thus no residual topography should be present between the two SAR acquisitions.

The displacement measurement through the DInSAR approach has the following main characteristics and requirements:
- The measurement accuracy is in the order of magnitude of centimeters per year (cm/year);
- It is mainly suited to measure displacement on wide areas and for intense event such as earthquakes;
- To run this tool the same sensor, the same geometry (Ascending/Ascending or Descending/Descending), the same incidence angle, the same data type and the co-polarized images (VV, HH) are mandatory;
- Displacement sensitivity depends on wavelength, which depends on sensors type. Data reliability depends on the object interaction. Moreover, the higher temporal changes, the lower reliability (i.e.

vegetation, snow, ice), above all for high frequency sensors. The reliability index is provided by the coherence product;

- The higher is the accuracy of the input DEM used to remove topographic phase contribution, the higher is the reliability of the estimated displacement;
- The selection of the temporal baseline should take into accounts the magnitude and the velocity of expected displacement. Slow displacement rates should be monitored with large temporal baseline, but a large baseline may lead to get low coherence over the analyzed area. At the same time a small baseline could not guarantee the sensitivity to detect the movement occurred between the two acquisitions.
- A small normal baseline is less sensitive to topographic variations; the Baseline estimation tool enables to obtain information about the baseline values and other orbital parameters related to the input pair (*Interferometry/Interferometric Tools/Baseline Estimation*);
- Sentinel-1 has been specifically designed to measure displacement thanks to his small orbit tube.

For Digital Elevation Model purposes it is necessary to make the assumption that the interferometric measure is totally relevant to topographic residuals, thus no displacement should have occurred between the two SAR acquisitions.

The DEM creation measurement through the DInSAR approach has the following main characteristics and requirements:

- To run this tool the same sensor, the same geometry (Ascending/Ascending or Descending/Descending), the same incidence angle, the same data type and co-polarized images (VV, HH) are mandatory;
- Low temporal baseline between is acquisition are strongly recommended in order to reduce as much as possible coherence drops;
- If the normal baseline is too small, these topographic effects on the differential phase are not pronounced enough. On the other hand too large baselines induce decorrelation effects; the critical baseline is the maximum value of baseline over which the interferometric correlation became zero. The Baseline estimation tool enables to obtain information about the baseline values and other orbital parameters related to the input pair (*Interferometry/Interferometric Tools/Baseline Estimation*). In any case, it is strongly suggested to use data pairs with a baseline value below half of the critical value.
- The Sentinel-1 mission was mainly designed for the retrieval of deformations (DInSAR) and not for DEM generation (*Geudtner et al. 2016*).

Processing steps overview

The DInSAR steps and sub-steps are described in the list below:

1. Interferogram Generation
2. Adaptive Filter and Coherence Generation
3. Phase Unwrapping
4. Refinement and Re-flattening
5. A - Phase to Height Conversion and Geocoding
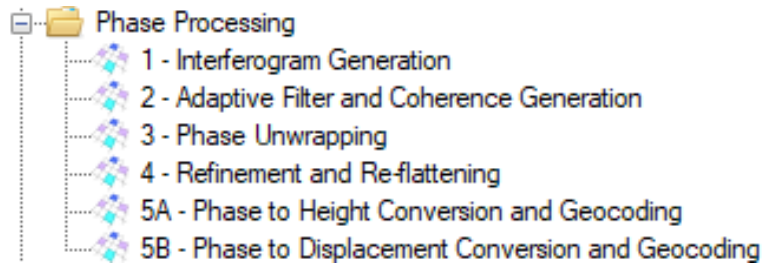5. B - Phase to Displacement conversion and Geocoding
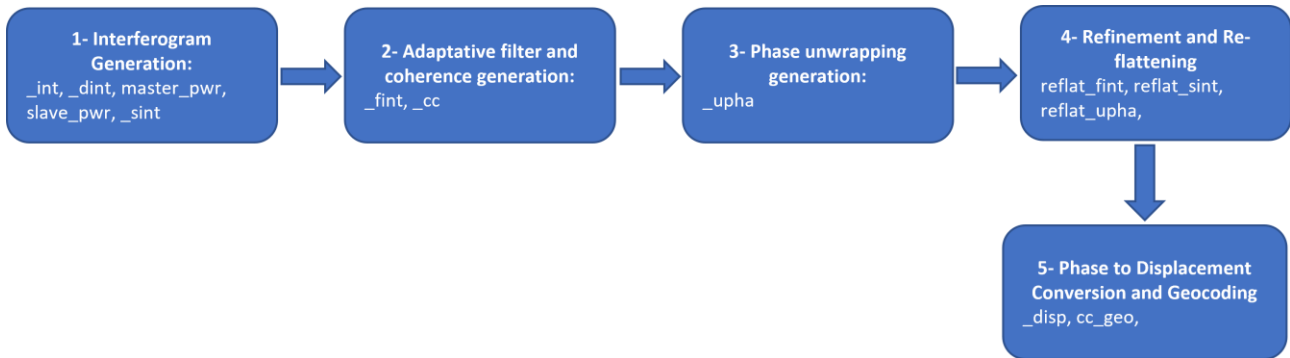
Figure 1 - Phase processing steps

Figure 2 Phase processing workflow and files generated for each step

Co-registration of the SAR image pair is required. The co-registration is the process of superimposing, in the slant range geometry, two or more SAR images that have the same orbit and acquisition mode.

After image co-registration, an interferometric phase is generated by multiplying one image by the complex conjugate of the second one. A complex interferogram, module and phase, is generated, whose module is generated by multiplying the input SAR images modules and the phase is generated by performing the phase difference between the input SAR images.

Due to the slightly different antenna positions, a systematic phase difference over the whole scene can be observed related to **the flat terrain**, the presence of topography may introduce **geometrical distortions** over the flat terrain one.

The flat earth component and the known terrain contribution can be removed by knowing the acquisition parameters of the two images used to generate the interferogram. This operation is called **Flattening**. The topography contribution can be removed by **subtracting a low resolution DEM** from the interferogram.

The phase signal, intended as the interferometric phase difference, may be affected by a certain level of noise; a parameter that helps to evaluate the phase stability of each pixel is the Coherence; it ranges between 0 and 1, where 0 means completely random phase signal, classified as noise, while coherence close to 1 indicates a stable phase signal commonly associated to Permanent scatterers points.

Noise filtering is applied to the generated interferograms (once flattened and the topography is removed), in order to calibrate and increase the precision of those pixel that may provide unreliable results.

Once the **filtering** is performed, the unwrapping procedure allows to obtain the absolute phase for those pixels whose coherence overcomes a defined threshold value.

The next DInSAR steps require a **refinement and re-flattening** process, it allows both to refine the orbits (i.e. correcting possible inaccuracies shown as residual systematic phase trends) and to calculate the phase offset (i.e. getting the absolute phase values).

The final step is the Phase to displacement or height conversion, the absolute calibrated and unwrapped phase values are converted to displacement or height and directly geocoded into a map projection.

The current tutorial is focused on the displacement measurement, a dedicated tutorial named ''Interferometry_DEM" covers the DEM creation part.

SARscape version	5.7.0
ENVI version	5.6.3
SO	64-bit Windows 10 Pro
RAM	32 GB
Processor	Intel (R) Core (TM) i9-9980HK CPU @ 2.40GHz
OpenCL	NVIDIA Quadro RTX 3000
HD	SSD EVO 2TB (as working directory)

2. Training Data sets description

On the 26th December 2003 an earthquake with MW=6.5 shook a large area of the Kerman Province in Iran. The epicenter of the devastating earthquake was located near the city of Bam. The earthquake was particularly destructive in Bam, with the death toll amounting to at least 34,000 people and injuring up to 200,000.

The displacement induced by this event will be analyzed thanks to the images acquired by the European satellite ENVISAT ASAR, on December 3rd 2003 (pre-event) and on February 11th 2004 (post-event).

The InSAR technique must be run separately for each acquisition geometry to permit a further possible displacement decomposition along the vertical and east-west directions.

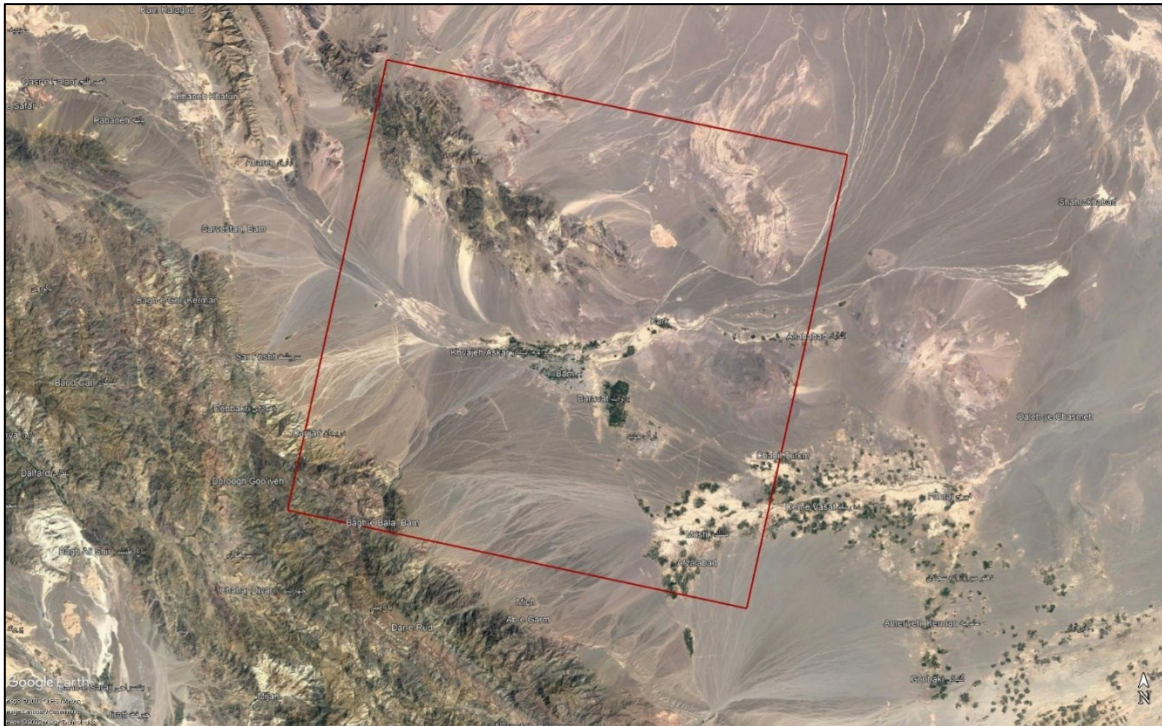In this tutorial, only the Descending (track 120) dataset is described.

Figure 3 Location of the Area of Interest, Bam area.

4. Before starting

Before starting to run the SBAS processing chain, it is strongly recommended to:

- set the ENVI Preferences.
- set the SARscape Preferences (Specific) based on the ENVISAT ASAR, MR (between 10m and 30m)
- read the Getting Started, Data Preparation and Basic Tutorial to become familiar with the basic processing chain that allows managing the dataset provided to run the DInSAR processing.

In fact, the dataset provided was downloaded, imported, and sampled using the corresponding SARscape tools.

The provided binary raster files are delivered with 3 auxiliary files:

- .hdr (an ASCII header for ENVI visualization)
- .sml (an ASCII header for SARscape processing with the main acquisition information)
- .kml (an ASCII file for Google Earth)

It is worth to mention that to apply the DInSAR technique users have to consider suitable sensors and acquisition modes.

The necessary steps to run a displacement DInSAR analysis are the following:
- Interferogram Generation
- Adaptative filter and coherence generation
- Phase unwrapping
- Refinement and Re-flattening
- Phase to displacement conversion and geocoding

All the details related to the description of the parameters are shown in grey in this document. The same information can be found on the specific help page of each panel.

Baseline estimation

The *Baseline Estimation* tool (Interferometry/Interferometric Tools/Baseline Estimation) is designed to establish if a pair of SAR images can be used for interferometric purposes. This tool enables us to obtain information about the baseline values and other orbital parameters related to the input pair, the extracted parameters have to be intended as approximate measurements aimed at a preliminary data characterization and interferometric quality assessment.

When the normal baseline exceeds the critical baseline value, no phase information is preserved, coherence is lost, and it is not possible to compute interferometric processes.

The sensibility to detect height variations is inversely proportional to the "2π ambiguity height": the bigger the ambiguity height the worse the capability to detect small elevation changes. The sensibility to detect displacements depends, instead, on the observation wavelength.

Run the tool Baseline Estimation tool:

Input Files

Input Reference file
File name of the Reference data (_pwr for ScanSAR products; _slc or _pwr for all the others). This file is mandatory.

Use as Reference image the BAM_asar-IMS_tr120_desc_20031203_rsp_slc

Input Secondary file
File name of the multi-looked coregistered Secondary Intensity data (_pwr). This file is mandatory.

Load the data BAM_asar-IMS_tr120_desc_20040211_rsp_slc as Secondary image.

Optional Files
Name of the output root. In addition to the results for the scene center that will shown up in the pop-up, this file includes the multilooked baseline, height of the ambiguity values and all other parameters for each pixel. This file is optional, if this field is empty, no output file will be created and only the values for the scene center are computed and shown up in the pop-up.

Set a customer output folder.

Click on the *Exec* button to run the tool.

A new window will appear, showing all the baseline details:

```
Baseline Estimation
File
Normal Baseline (m) = 3.731      Critical Baseline min - max(m) = [-985.267] - [985.267]
Range Shift (pixels)    = 1.791
Azimuth Shift (pixels)  = -1172.593
Slant Range Distance (m)  = 851937.979
Absolute Time Baseline (Days) = 70
Doppler Centroid diff. (Hz) = -33.982    Critical min-max (Hz) = [-1652.416] - [1652.416]
2 PI Ambiguity height (InSAR) (m) = 2593.744
2 PI Ambiguity displacement (DInSAR) (m) = 0.028
1 Pixel Shift Ambiguity height (Stereo Radargrammetry) (m) = 719882.061
1 Pixel Shift Ambiguity displacement (Amplitude Tracking) (m) = 7.804
Reference Incidence Angle = 23.828      Absolute Incidence Angle difference = 0.000
Potentially suitable for Interferometry or Amplitude Tracking
```

Figure 4 Baseline estimation output.

Normal Baseline (m) = 3.731　　　　**Critical Baseline min - max(m) = [-985.267] - [985.267]**

Range Shift (pixels)   = 1.791

Azimuth Shift (pixels) = -1172.593

Slant Range Distance (m)   = 851937.979

Absolute Time Baseline (Days) = 70

Doppler Centroid diff. (Hz) = -33.982   Critical min-max (Hz) = [-1652.416] - [1652.416]

2 PI Ambiguity height (InSAR) (m) = 2593.744

2 PI Ambiguity displacement (DInSAR) (m) = 0.028

1 Pixel Shift Ambiguity height (Stereo Radargrammetry) (m) = 719882.061

1 Pixel Shift Ambiguity displacement (Amplitude Tracking) (m) = 7.804

Reference Incidence Angle = 23.828   Absolute Incidence Angle difference = 0.000

Potentially suitable for Interferometry or Amplitude Tracking

The sentence ''Potentially suitable for Interferometry or Amplitude Tracking'' is printed in case the image pair can be used for interferometric purposes.

This specific pair has an 2 *PI Ambiguity displacement* of around 0.028 meters, i.e. one fringe correspond to a variation of 2.8 centimeters that is half of the wavelength of the SAR sensor.

5. Interferogram Generation

The *Interferometric Generation* process step creates the multi-looked wrapped interferogram through a few sub-steps: *co-registration, differential interferogram generation, flattening* and optional *phase pattern removal* and *unwrapping*.

The *Interferometric Process* is performed running the *Interferometry/Phase Processing/1 - Interferogram Generation* panel (see Figure 5).

Input files

Select the Reference and Secondary images.

Use the earlier date as Reference image BAM_asar-IMS_tr120_desc_20031203_rsp_slc and the older one as Secondary one BAM_asar-IMS_tr120_desc_20040211_rsp_slc.

Optional file

Leave the Geometry GCP File empty.

Leave Shift Parameters File empty.

Leave ScanSAR-TOPSAR Spectral Diversity Avoid Moving Area empty.

DEM/Cartographic System

Insert the dem_srtmV4_BAm_dem provided in the dataset.

Principal Parameters

Range Looks
Number of looks in range referred to the Reference.

Azimuth Looks
Number of looks in azimuth referred to the Reference.

Grid Size for Suggested Looks.
The grid size, in meters, used to tune range and azimuth looks. If the other parameters are manually set, the grid size will not imply a change in their values..

Compute Shift Parameters
By setting this flag, the coregistration shifts between reference and secondary image are calculated and saved into the _par file.

Generate Coregistered SLC
By setting this flag, reference and secondary coregistered Single Look Complex data are generated among the output products. These files are over sampled by a factor of 2 in range direction.

Coregistration with DEM
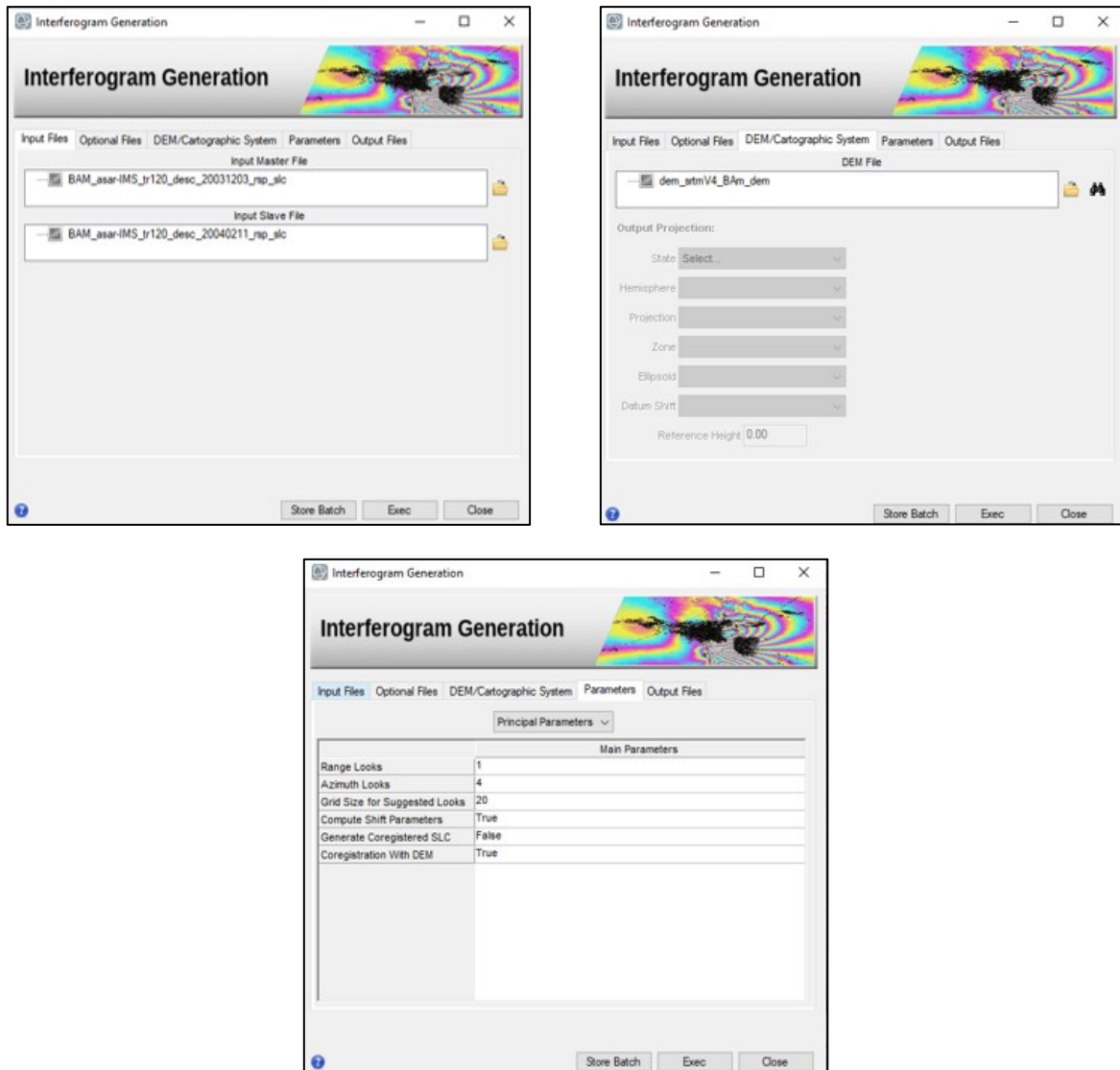By setting this flag, the input Digital Elevation Model is used in the co-registration process.

Figure 5 *Interferogram Generation* panels.

Output
The output folder contains the following products:

- *_int*
  Interferogram with the associated header files (.sml, .hdr).

- *_dint*
  Flattened interferogram with the associated header files (.sml, .hdr).

- *_dint_ql.tiff and/or _dint_qlt.tiff*
  Tiff image of the flattened interferogram. The creation of these files depends on the selection of "quick look format" in the parameters.

- *_sint*
  Synthetic phase with the associated header files (.sml, .hdr).

- *_srdem*
  Digital Elevation Model, in slant range geometry, with the associated header files (.sml, .hdr).

- *_slc_rsp*
  Coregistered Single Look Complex data. This file is generated only if the relevant flag is set.

- _par

  ASCII file containing the coregistration shift parameters in range and azimuth. This file is generated only if the shift parameters are calculated.

- _pwr

  Multi-looked reference and secondary image with the associated header files (.sml, .hdr).

- _orb.sml

  Xml file containing the scene orbital parameters.

- _orbit_off.shp

  Shape file with the points used to estimate the orbit based shift. This file contains the following information:

  - Pixel position in range direction (Range), in Single Look pixel units.
  - Pixel position in azimuth direction (Azimuth), in Single Look pixel units.
  - Shift measured in range direction (Dr), in Single Look pixel units.
  - Shift measured in azimuth direction (Da), in Single Look pixel units.
  - Pixel position in range direction (Range), in Single Look pixel units.
  - Pixel position in azimuth direction (Azimuth), in Single Look pixel units.
  - Calculated polynomial shift, to apply in range direction (Drfit), in Single Look pixel units.
  - Calculated polynomial shift, to apply in azimuth direction (Dafit), in Single Look pixel units.

- _winCC_off.shp

  Shape file with the points used to estimate the cross correlation based shift from the Intensity data. In addition to the information provided by the "_orbit_off.shp" file, this file contains also the cross-correlation value (CC), which is dimensionless and it can vary from 0 to 1.

- winCoh_off.shp

  Shape file with the points used to estimate the coherence based shift from the complex data (fine shift estimate). In addition to the information provided by the "_orbit_off.shp", this file contains also the following information:

  - Signal to Noise Ratio (SNR), which is a linear dimensionless value.
  - Coherence value. It is dimensionless and it can vary from 0 to 1.

The software automatically displays the flattened interferogram together with the power image of the Reference and Secondary data.
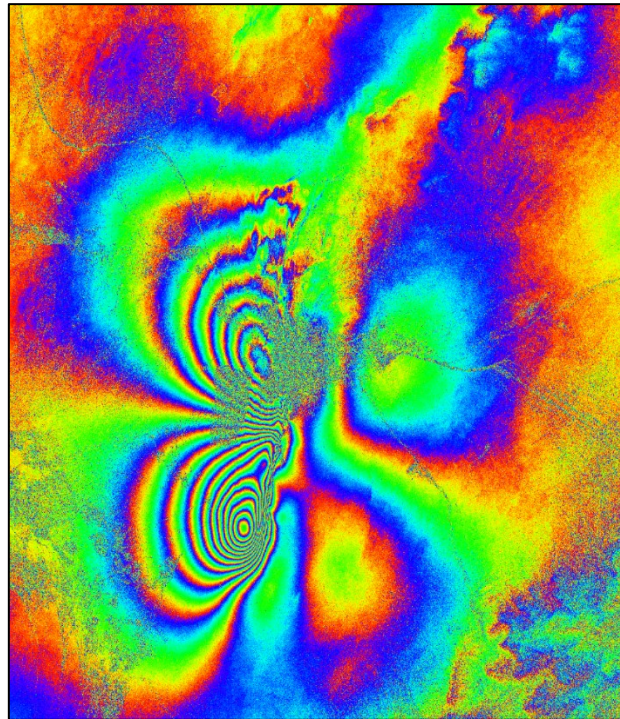
Figure 6 Flattened interferogram, in slant range geometry, colored with the ENVI Rainbow color scale (_fint).

Each fringe in the interferogram corresponds to ground deformation equal to 2,8 cm.

Observing the above interferogram anomalous behavior, such as inaccurate orbits phase ramp, un-coherent pairs, atmospheric artifacts, residual topography effects, can be detected.

In the next chapter GACOS data will be used to mitigate the atmospheric artifact effects.

6. Atmospheric Phase Delay Correction

GACOS utilizes the Iterative Tropospheric Decomposition (ITD) model (Yu et al., 2017) to separate stratified and turbulent signals from tropospheric total delays, and generate high spatial resolution zenith total delay maps to be used for correcting InSAR measurements and other applications. More details on GACOS data can be found at the following link: http://www.gacos.net/ GACOS data allows the improvement of the atmospheric correction within the interferometric processing.

See *Annex 3. GACOS Data Usage* to get more information on the GACOS data management.

The workflow for atmosphere removal through GACOS is the following:

- GACOS data have to be downloaded manually from the following website: http://www.gacos.net/, one GACOS data for each SAR image.
- Then this data need to be imported in SARscape through the tool *Import Data/Other Format/GACOS,* at this stage the ztd_geo file are created.
- Open the tool *Interferometry/Interferometric Tools/Atmospheric Phase Delay Correction* and insert the GACOS ztd_geo files within the Optional Files panel. It is also necessary to set the *Atmosphere External Sensors* within the Parameters panel (Figure 7Figure 3). The tool will remove the atmosphere artefacts from the input file (_dint).

Input files

Interferogram file
File name of the previously generated interferogram (_dint or _fint). This file is mandatory.

Load the previously created _dint file.

Slant Range Digital Elevation Model file
Name of the Digital Elevation Model in slant range geometry (_srdem). This file is mandatory.

Optional Files

Optional Reference Water Vapour File
File name of the reference water vapour data or data file list (_filename_list.txt; *_bil). This file is mandatory only when the MERIS or GACOS sensor type is used.

Load the 20031203_ztd_geo file.

Optional Secondary Water Vapour File
File name of the secondary water vapour data or data file list (_filename_list.txt; *_bil). This file is mandatory only when the MERIS or GACOS sensor type is used.

Load the 20040211_ztd_geo file.

Unwrapped Phase File
Name of the unwrapped phase (_upha). This file is mandatory only when the Atmosphere Height Correlation Flag is selected.

Leave this field empty.

DEM/Cartographic System

Insert the dem_srtmV4_BAm_dem provided in the dataset.

Principal Parameters

Atmosphere External Sensors
By inserting this optional list, the software removes the atmosphere artefacts from the filtered interferogram stack using external sensors such as GACOS and MERIS (only for ENVISAT data).

Select GACOS.

Atmosphere Height Correlation Flag
By selecting this flag, the algorithm estimates and removes the height-related component of the atmosphere from each interferogram, using a the "Height Correlation Window Size [m]" (Atmosphere section) parameter to define the size of the filter. To enable this flag is mandatory to upload an _upha file within the Unwrapped Phase File filed.

Output

The output folder contains the following products:

Output Root Name
Name of the output root. This file is mandatory.

_corr_dint/fint

Corrected interferogram with the associated header files (.sml, .hdr).

_corr_mask

MERIS masked reference and secondary data, in the original image geometry, with the associated header files (.sml, .hdr).

_corr_atm

Atmospheric phase delay, in slant range SAR reference image geometry, with the associated header files (.sml, .hdr).
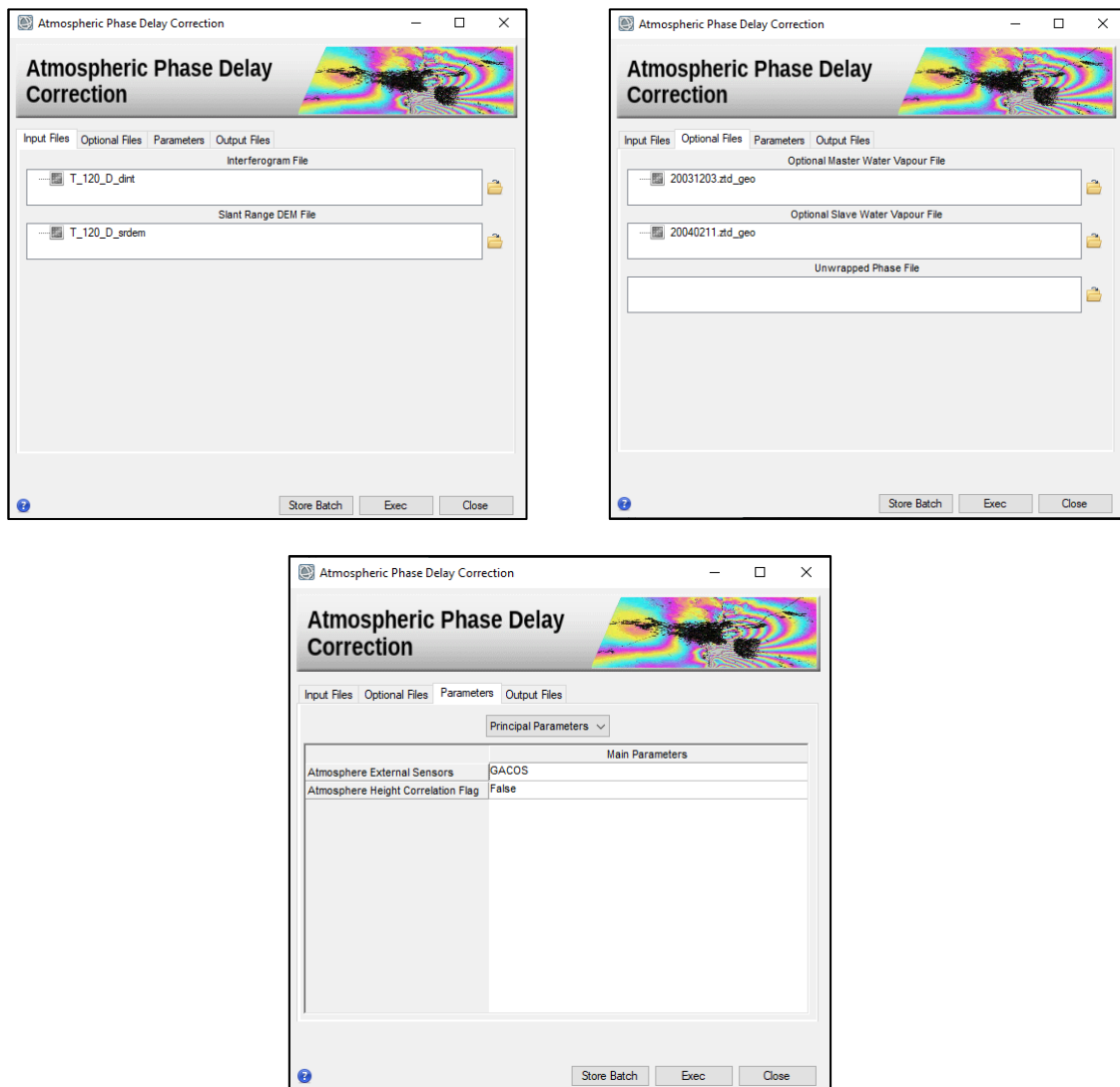

Figure 7 *Atmospheric Phase Delay Correction* panels.

The corrected flattened interferogram has a lower number of fringes compared to the flattened interferogram, the correction acts especially on the low-frequency fringes, visible in the upper-right and left side of image (Figure 7).
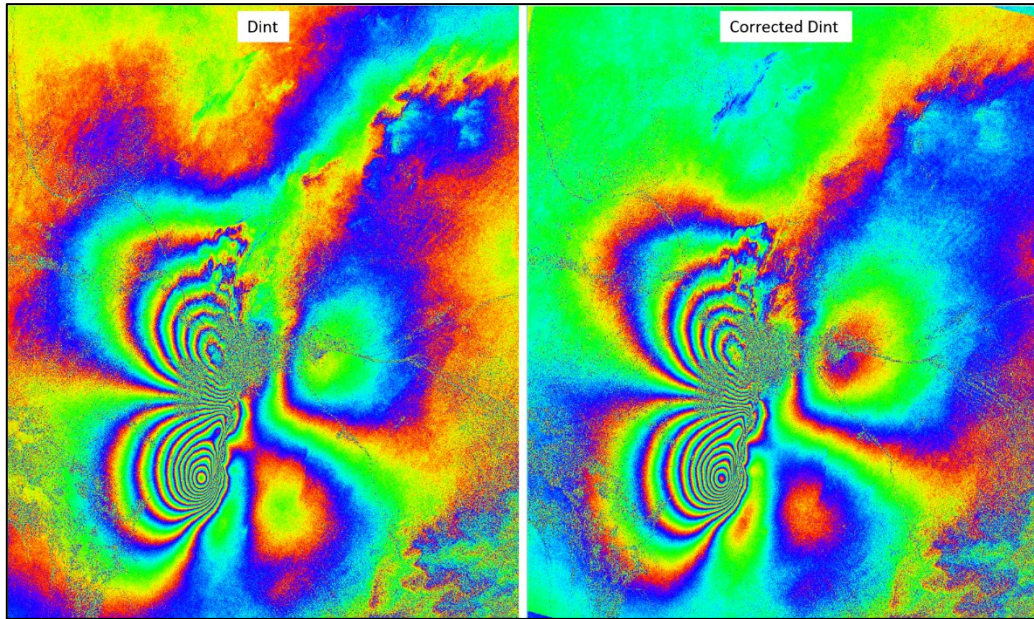
Figure 8 Flattened interferogram (_dint), on the left, vs atmosphere corrected and flattened interferogram (_dint_corr), on the right.

7. Adaptative Filter and Coherence Generation

Coherence is computed between a pair of SAR acquisitions, and refers to the phase stability on a certain pixel estimated through a complex cross correlation over the interferometric neighboring pixels; it ranges between 0 and 1, where 0 means completely random phase signal, classified as noise, while coherence close to 1 indicates a stable phase signal commonly associated to Permanent scatterers points.

Coherence data have two major applications:

- To determine the quality of the phae measurement (i.e. interferometric phase). Usually, interferograms generated from data with coherence lower than around 0.2 should not be considered for the further processing and will be considered as noise.

- To extract thematic information for land cover characterization. This analysis is typically performed by combining coherence and backscattering coefficient.

Noise filtering is applied to the generated interferogram (after flattening, topographic removal and atmospheric correction), in order to calibrate and increase the precision of those pixel that may provide unreliable results. Several different types of filters can be applied, such as: Goldstein, Boxcar or the Adaptive Non Local filter, this last one is the most precise filtering method and it requires the usage of a GPU to work rapidly. Further processing tools allow to apply atmospheric corrections through the usage of external data, such as GACOS data, or to remove polynomial phase trend, low frequency phase components or height correlated phase distortions.

The filtering of the flattened interferogram enables to generate an output product with reduced phase noise. The Interferometric Coherence and the Reference Intensity filtered image, are also generated.

The *Adaptative Filter and Coherence Generation* is performed after running the *Interferometry/Interferometric Tools/Atmospheric Phase Delay Correction* panel (see Figure 9).

Input files

Interferogram file
File name of the previously generated interferogram (_dint or _fint). This file is mandatory.

Load the previously created _corr_dint file.

Input Reference file
File name of the multi-looked reference Intensity data (_pwr). This file is mandatory.

Load the reference_pwr file.

Input Secondary file
File name of the multi-looked coregistered secondary Intensity data (_pwr). This file is mandatory.

Load the secondary_pwr file.

Principal Parameters

Coherence Generation
By setting this flag, the coherence is generated.

Adaptive Filter

By setting this flag, the input interferogram is filtered. This flag is disabled when the "Local Frequency Removal (Range and Azimuth)" is set to a value higher than zero.

Filtering method

The choice is given between the following filtering methods according to the default values of the filtering section of the Preferences parameters:

- ➢ Adaptive window;
- ➢ Boxcar window;
- ➢ Goldstein.

Coherence from Fint

By setting this flag, the coherence is computed using the filtered interferogram (_fint) instead of the unfiltered one (_dint).

Output

The output folder contains the following products:

Output Root Name
Name of the output root. This file is mandatory.

_fint
Filtered interferogram with the associated header files (.sml, .hdr). This file is generated only if the Adaptive Filter flag is selected.

_fint_ql.tiff and/or *_fint_qlt.tiff*
Tiff image of the filtered interferogram. The creation of these files depends on the selection of "quick look format" in the parameters.

_pwr_fil
Filtered Intensity - from reference and secondary combination - with the associated header files (.sml, .hdr). This file is generated only if the "Adaptive" filter is selected.

_cc
Estimated coherence with the associated header files (.sml, .hdr). This file is generated only if the Coherence Generation flag is selected.
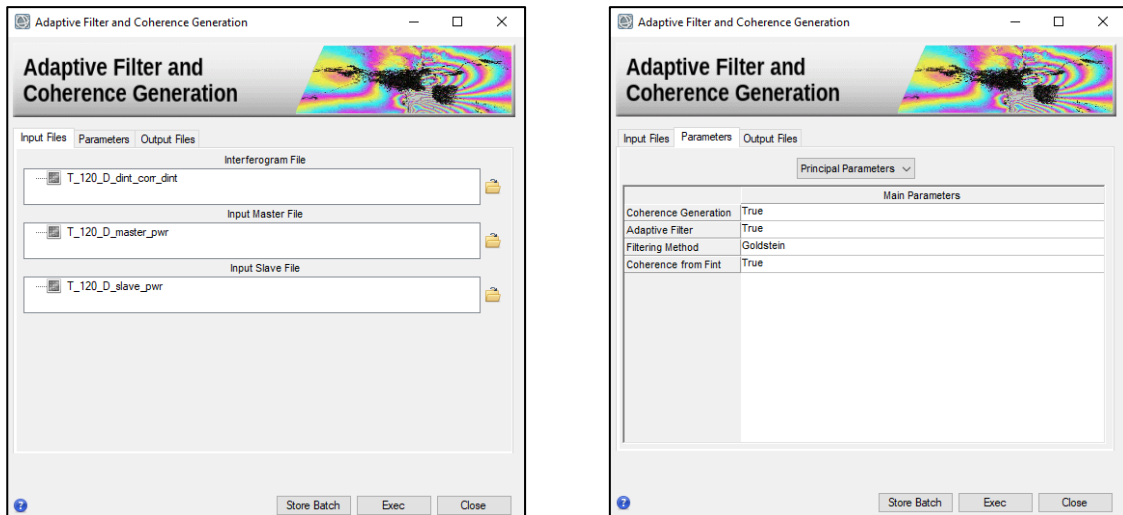
Figure 9 Adaptative Filter and Coherence Generation panels.

The central part of the image shows the lowest values of coherence (darker areas), this is likely due to the surface change as consequence of the earthquake that causes a coherence drop between the two images. The other dark areas are likely related to the presence of water bodies or crop fields. (Figure 7).
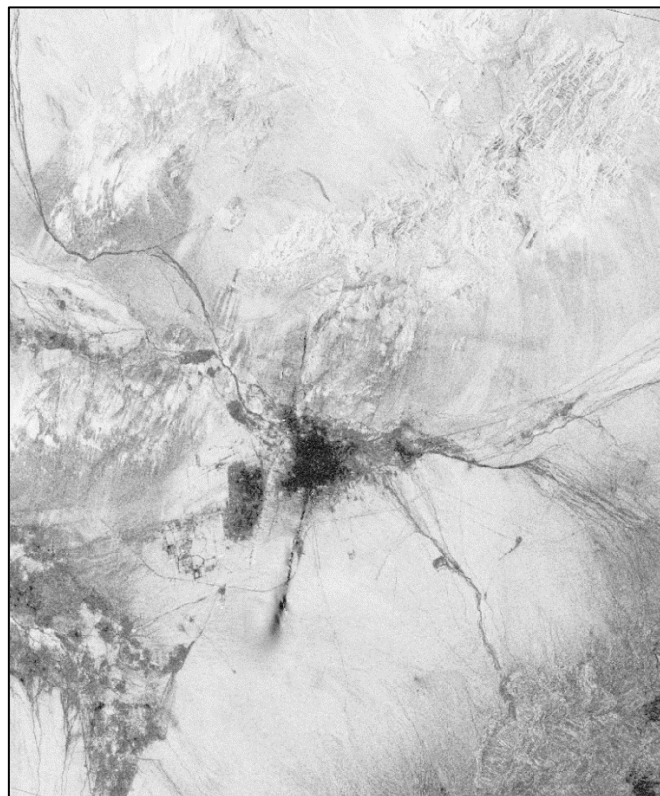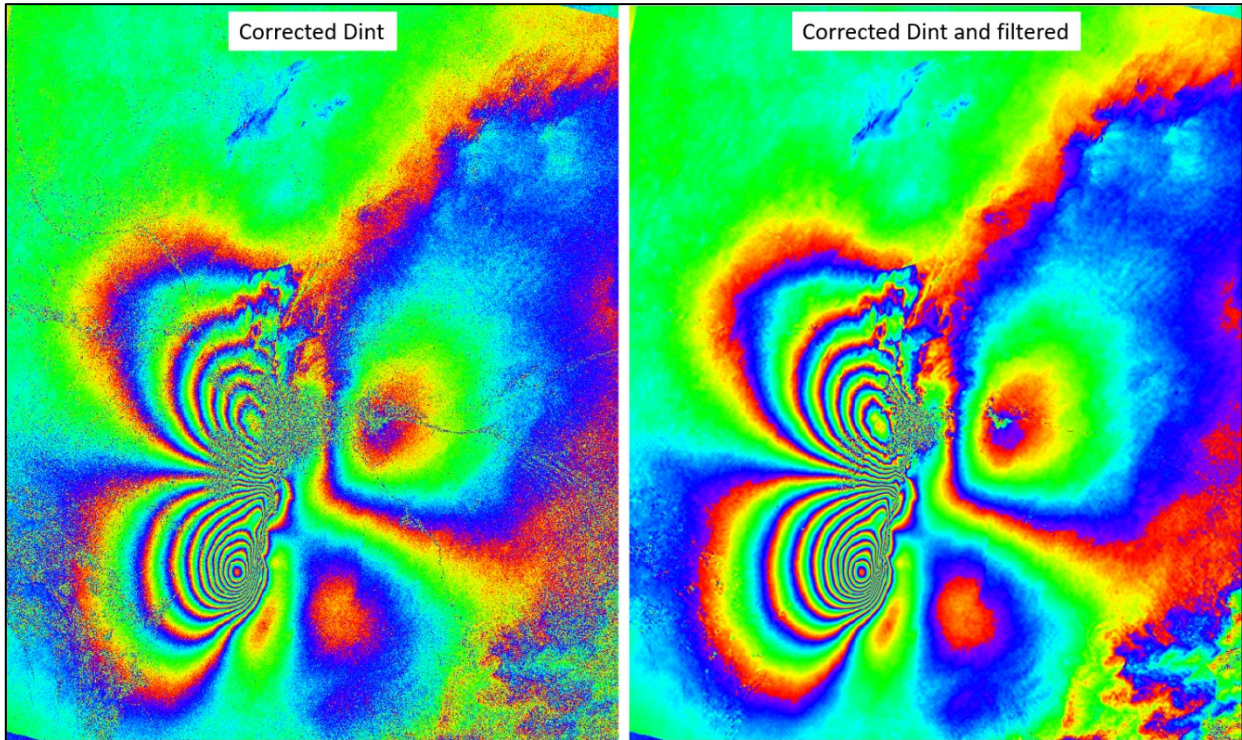

Figure 10 Coherence image (_cc)

Figure 11 Atmosphere corrected flattened interferogram (_dint_corr), on the left, corrected flattened and filtered interferogram on the right (_fint).

8. Phase Unwrapping

The phase of the interferogram can only be modulo 2π; hence anytime the phase change becomes larger than 2π the phase starts again and the cycle repeats itself. Phase Unwrapping is the process that resolves this 2π ambiguity. Several algorithms (such as the branch-cuts, region growing, minimum cost flow, minimum least squares, multi-baseline, etc.) have been developed; in essence, none of these is perfect and different approaches should be applied on a case by case basis to get optimal results.
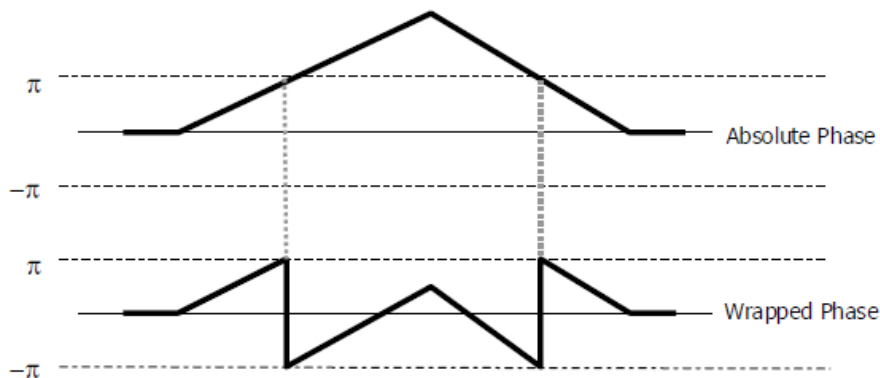
Figure 12 Wrapped Phase vs Absolute Phase sketch

Input files

Coherence file
File name of the coherence (_cc). This file is mandatory.

Interferogram file

File name of the flattened - and possibly filtered - interferogram (_fint). This file is mandatory.

Principal Parameters

Unwrapping Method Type

The choice is given between the following unwrapping methods:

- *Region Growing*, the Region Growing unwrapping method is used;
- *Minimum Cost Flow*, the Minimum Cost Flow (square grid) unwrapping method is used;
- *Delaunay MCF*, the Minimum Cost Flow (triangular grid) unwrapping method is used.

Unwrapping Decomposition Level

The number of under sampling levels to be applied to the complex interferogram before performing the phase unwrapping can be specified (refer to the Technical Note).

Unwrapping Coherence Threshold

Pixels with coherence values smaller than this threshold are not unwrapped.

Output

The output folder contains the following products:

Unwrapped Phase file

File name of the output unwrapped phase. This file is mandatory.

_upha

Unwrapped phase with the associated header files (.sml, .hdr).

_reflat_upha

Re-flattened unwrapped phase with the associated header files (.sml, .hdr). This file is generated only for Tandem-X bistatic Data.
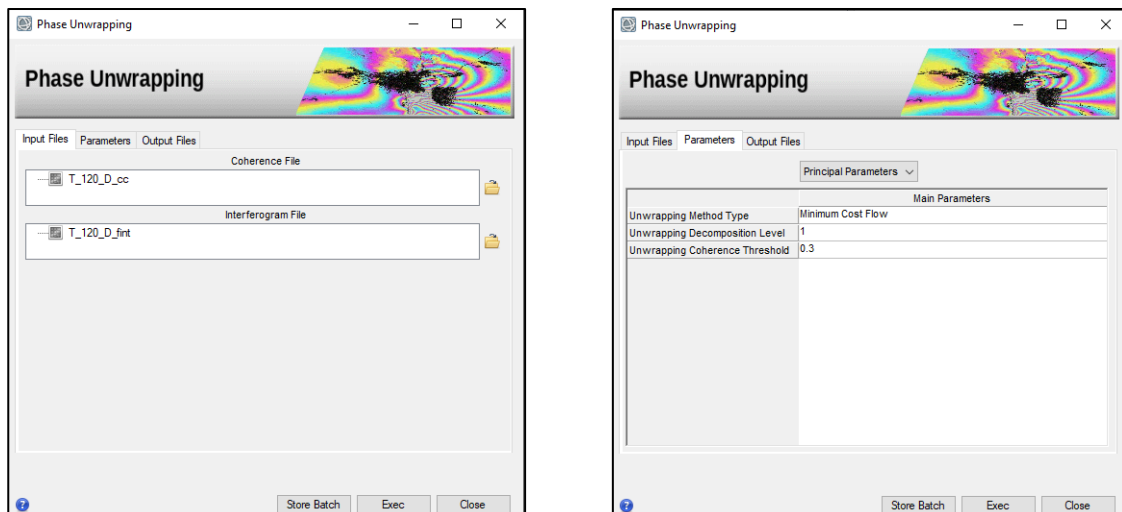

Figure 13 Phase Unwrapping panels.

The data gap visible in the central part of the unwrapped image is due to coherence values lower than the threshold configured by the user, that in this case corresponds to 0.3 (Figure 14).
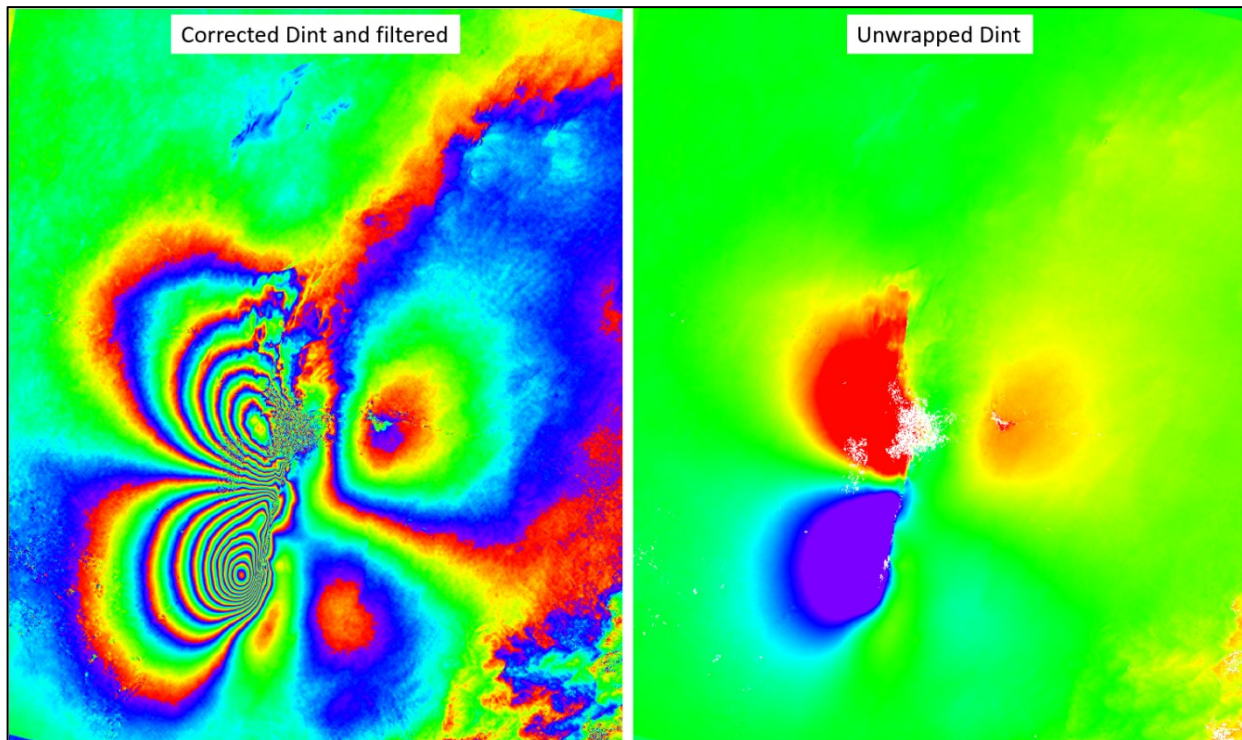
Figure 14 Corrected flattened and filtered interferogram (_dint), on the left, unwrapped dint on the right (_upha).

9. Refinement and Re-flattening

This step is crucial for a correct transformation of the unwrapped phase information into displacement values. It allows both to refine the orbits (i.e. correcting possible inaccuracies) and to calculate the phase offset (i.e. getting the absolute phase values), or remove possible phase ramps.
The execution of this step is mandatory for Digital Elevation Model generation as well as for Displacement Mapping.
This dataset doesn't show the presence of phase ramps that need to be removed, therefore it is sufficient to place one single GCP that will correspond to the point with zero displacement, and the measurements will be referred to that point.

N.B: For more complex scenarios where phase ramps are present, it is suggested to insert at least 40 GCP points.

Input files

Coherence file
Name of the coherence image (_cc). This file is mandatory if a "Refinement Method" is selected.

Input Reference file
File name of the multi-looked reference Intensity data (_pwr). This file is mandatory.

Input Secondary file
File name of the multi-looked coregistered secondary Intensity data (_pwr). This file is mandatory.

Unwrapped Phase file
Name of the unwrapped phase (_upha). This file is mandatory.

Synthetic Phase file

Name of the synthetic phase (_sint). This file is mandatory.

Slant Range Digital Elevation Model file
Name of the Digital Elevation Model in slant range geometry (_srdem).

Refinement GCP file
Either a previously created Ground Control Point file (.xml) is loaded (Load GCP File), or the interface to create a new Ground Control Point file is automatically loaded (Create GCP File, refer to the "Tools>Generate Ground Control Point" for details). This file is mandatory if a "Refinement Method" is selected.

Click on the binocular button to start the Generate Control Points process.

Optional Files

Interferogram file
Name of the flattened phase (_fint, _dint). This file is optional.

DEM/Cartographic System

Digital Elevation Model file
Name of the Digital Elevation Model file (geocoded reference DEM). This file is mandatory if it had been used as input for the flattened interferogram generation. If the Digital Elevation Model is omitted, an ellipsoidal height including the cartographic reference system must be set.

Output Projection
In case that the Digital Elevation Model is not used, the following parameters are compulsory to define the Cartographic System:

State
Definition of the country or general projection systems.

Projection
Definition of the projection system of the selected State. In case that a general projection system is selected in State, the Projection is automatically set.

Ellipsoid
Definition of the ellipsoid. This is chosen according to the selected State and Projection.

Hemisphere
Definition of the hemisphere. This is chosen according to the selected State and Projection.

Zone
Definition of the zone. This is chosen according to the selected State and Projection.

Datum Shift Parameters
Definition of the datum shift parameters. These are chosen according to the selected State and Projection.

Reference Height
In case that the Digital Elevation Model is not used, a constant ellipsoidal height must be provided. Default Reference Height is 0.

Cartographic Parameters
The reference parameters for some projection systems (e.g. Stereographic, Polar Stereographic, Gnomonic, Mercator, Miller, Albers, etc.) can be set.

Principal Parameters

Refinement method
The choice is given between the following refinement methods:

- Automatic Refinement;
- Polynomial Refinement;
- Orbital Refinement.

Refer to the flattening section of the Preferences for further information about these methods.

Refinement Residual Phase Polynomial Degree
Degree of the polynomial used to estimate the phase ramp, which will be removed from the input unwrapped phase during the Re-flattening operation. In case this value is higher that the number of input Ground Control Points, it will be automatically decreased. The default values of 3 means that a phase ramp in range and azimuth direction plus a constant phase offset will be corrected. In case only the phase offset correction is needed, the polynomial degree will be set to 1.

Coregistration With DEM
This parameter can not be defined by the user.

Output

The output folder contains the following products:

Output Root Name
Name of the output root. This file is optional.

_reflat_dint/fint
Re-flattened interferogram with the associated header files (.sml, .hdr).

_reflat_sint
Re-flattened synthetic phase with the associated header files (.sml, .hdr). This file is generated only if a "Refinement Method" was selected.

_reflat_upha
Re-flattened unwrapped phase with the associated header files (.sml, .hdr).

_reflat_srdem
Digital Elevation Model, in slant range geometry, with the associated header files (.sml, .hdr). This file is generated only if a "Refinement Method" was selected.

_reflat.txt
Text file with the orbital correction parameters resulting from the refinement.

_refinement.shp
Shape file containing those points retained (valid GCPs) form the input "Refinement GCP file".

_refinement_geo.shp
Shape file containing the geocoded location of the valid GCPs used in the refinement process.

The following information is provided if the "Orbital" method is applied:

The most important criteria to select the GCP point's location on the unwrapped phase files are the following:

- The GCP should be located within an area without displacement fringes, hence remain quite far from the displacement area, if known. The displacement rate of the selected GCPs is considered to be 0, unless a known displacement rate is provided in input, as for example as resulting from external measurements.

- There should be no phase jumps corresponding to unwrapping errors. If a point is located inside an isolated phase "island", with poorly unwrapped value, it might be considered as part of a phase ramp and resulting in an overall wrong correction.

- If the fint shows systematic acquisition geometry errors (orbit imprecision), the GCPs should then cover the entire track/frame (always following the criteria listed above) in order to remove this effect.

More details on the GCP creation process can be found in the GCP Manual, page 14, available on the sarmap website: https://www.sarmap.ch/tutorials/GCP_Manual_V_1_1.pdf

Select one single point located in a high coherence areas far away from the displacement area (Figure 15).
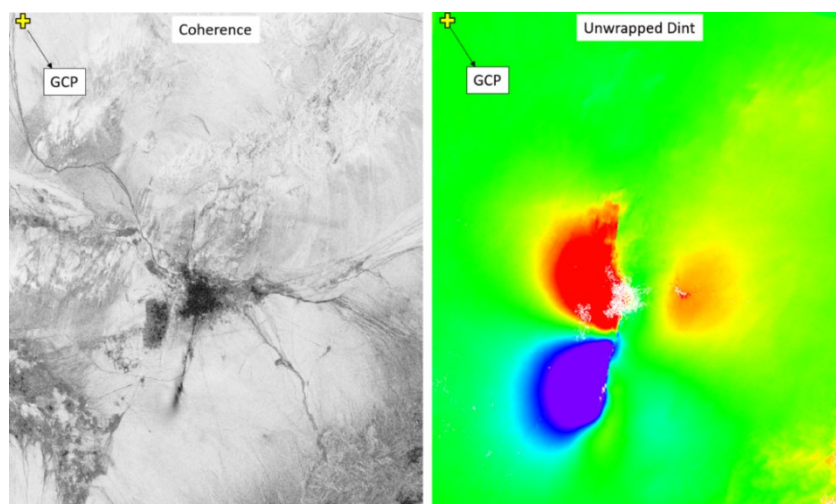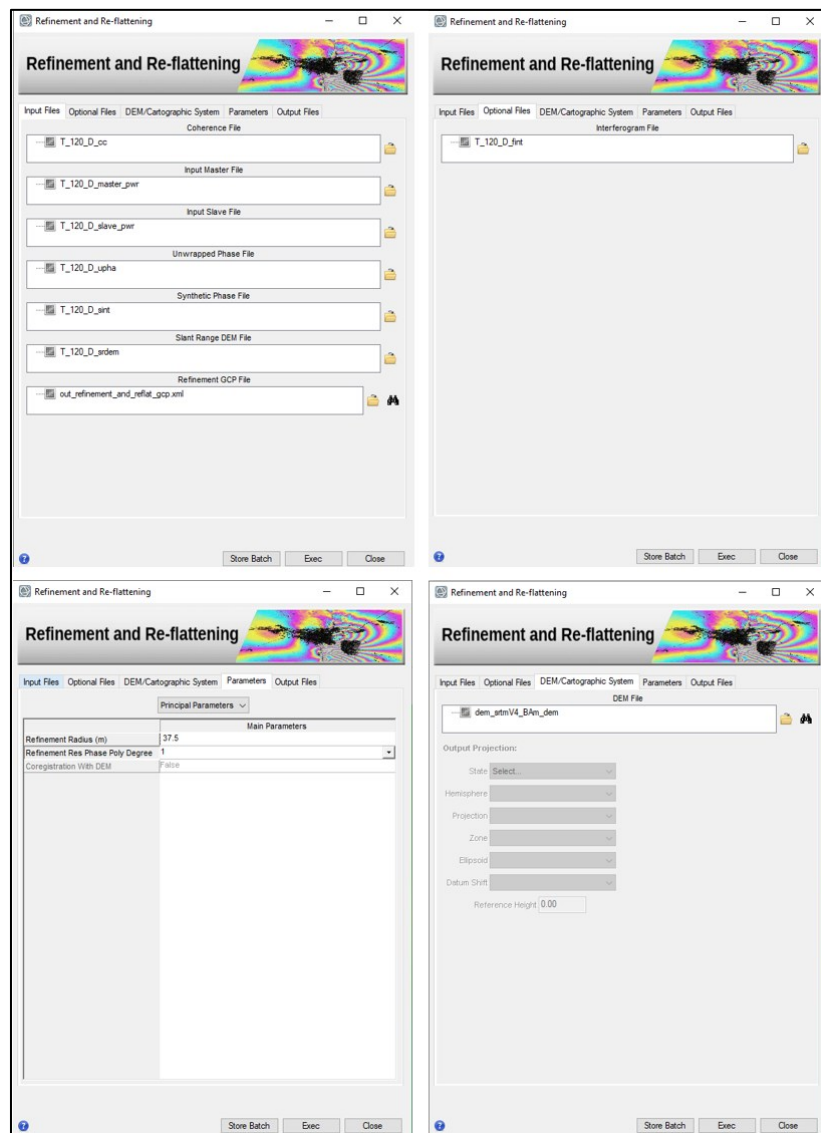

Figure 15 GCP position

Figure 16 Refinement and Re-flattening panels.

When a single GCP point is chosen, the polynomial correction consists on the removal of a constant value on the entire interferogram. While in case multiple GCPs grouped in a specific area, it is then necessary to manually set the ''Refinement Res Phase Poly Degree'' to 1, in order to avoid having wrong polynomial fit in the rest of the interferogram.

10. Phase to Displacement Conversion and Geocoding

The absolute calibrated and unwrapped phase values are converted to displacement and directly geocoded into a map projection. This step is performed by considering the Range-Doppler approach and the related geodetic and cartographic transforms.

As result of this step also the coherence image is geocoded.

The output map shows displacement magnitude in meters:

- Slant Range Displacement - Positive sign if the movement corresponds to a decrease of the sensor-to-target slant range distance (the most recent image respect to the older acquisition).
- Vertical Displacement - Positive sign corresponds to a decrease of the sensor-target distance reprojected along the vertical direction are generated among the output products.
- Slope Displacement - Positive sign corresponds to a decrease of the sensor-target distance reprojected along the maximum slope direction are generated among the output products.
- Displacement Custom Direction - Positive sign corresponds to a decrease of the sensor-target distance reprojected along the user defined the user defined direction (the most recent image respect to the older acquisition).

The combination of data obtained from at least two different orbits (ascending and descending), acquired over the same area in the same period, allows the estimation of vertical and east-west movement

Note that the displacement occurring along the Nord-South direction can not be measured since SAR satellites fly with a polar orbit and thus parallel to the North-South direction.
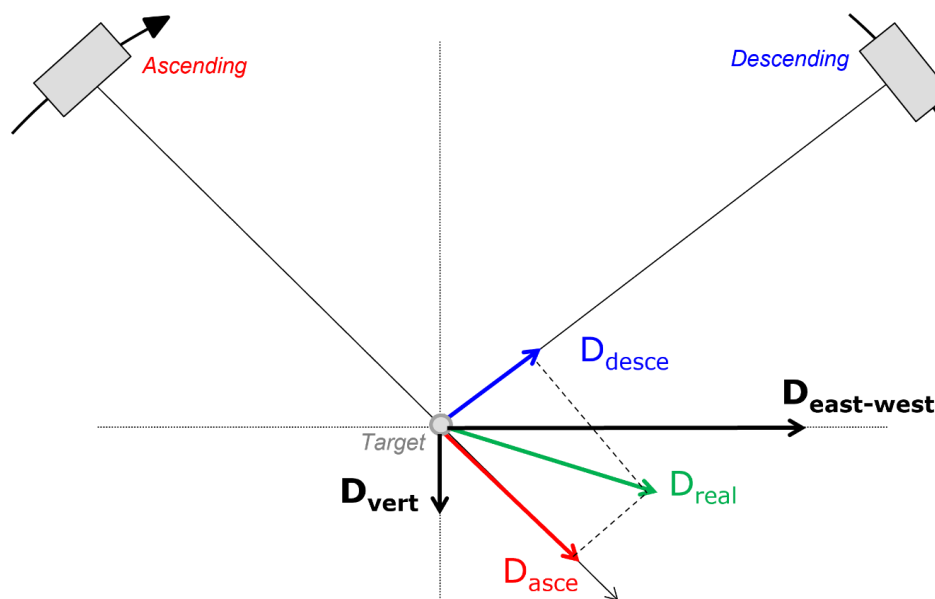

Figure 17 2D displacement decomposition

Input Files

Coherence file
File name of the coherence (_cc). This file is optional.

Unwrapped Phase file
File name of the reflattened unwrapped phase (_upha). This file is mandatory.

DEM/Cartographic System

Digital Elevation Model file
Name of the Digital Elevation Model file. This should be referred to the ellipsoid. This file is optional. In case it is omitted, the ellipsoidal height and the relevant cartographic reference system, must be entered.

Output Projection
In case that the Digital Elevation Model is not used, the following parameters are compulsory to define the Cartographic System:

    State

Definition of the country or general projection systems.

Projection
Definition of the projection system of the selected State. In case that a general projection system is selected in State, the Projection is automatically set.

Ellipsoid
Definition of the ellipsoid. This is chosen according to the selected State and Projection.

Hemisphere
Definition of the hemisphere. This is chosen according to the selected State and Projection.

Zone
Definition of the zone. This is chosen according to the selected State and Projection.

Datum Shift Parameters
Definition of the datum shift parameters. These are chosen according to the selected State and Projection.

Cartographic Parameters
The reference parameters for some projection systems (e.g. Stereographic, Polar Stereographic, Gnomonic, Mercator, Miller, Albers, etc.) can be set.

Parameters - Principal Parameters

Product Coherence Threshold
Pixels with coherence values smaller than this threshold will be set to dummy (NaN) in the final products.

Vertical Displacement
By setting this flag the map showing the displacement values projected on the vertical direction is generated among the output products.

Slope Displacement
By setting this flag the map showing the displacement values projected along the maximum slope is generated among the output products.

Displacement Custom Direction
By setting this flag any vector can be specified, in terms of azimuth (Azimuth Angle, measured in degrees from the North - clockwise direction) and inclination (Inclination Angle, measured in degrees from the horizontal plane). The map showing the displacement values projected on the specified direction is generated among the output products.

X Dimension (m)
The grid size of the output data in Easting (X) must be defined; the default unit of measure is meters.
Note that - for the Geographic projection - if values higher than 0.2 are entered they will be considered as metric units and then automatically, and roughly, converted from meters to degrees; if values lower than 0.2 are entered they will be considered as degree and used as such without any conversion.

Y Dimension (m)
The grid size of the output data in Northing (Y) must be defined; the default unit of measure is meters.
Note that - for the Geographic projection - if values higher than 0.2 are entered they will be considered as metric units and then automatically, and roughly, converted from meters to degrees; if values lower than 0.2 are entered they will be considered as degree and used as such without any conversion.

Interpolation Window Size
By setting this flag the dummy values in the output file are interpolated. The interpolated value is the average of the valid values in a window of the size selected.

Dummy Removal

By setting this flag the output geocoded files will be automatically resized in order to remove the dummy area exceeding the frame border.

Output Files

The output folder contains the following products:

Output Root Name

Name of the output root. It is mandatory.

_dem

Input Digital Elevation Model resampled onto the specified cartographic system and grid size, with the associated header files (.sml, .hdr). Its areal extent is the same as the output SAR products.

_cc_geo

Geocoded coherence with the associated header files (.sml, .hdr).

_ADF

Maximum slope direction values, with the associated header files (.sml, .hdr).

_IDF

Maximum slope inclination values, with the associated header files (.sml, .hdr).

_SD

Displacement values along the maximum slope direction, with the associated header files (.sml, .hdr).

_UD

Displacement values in the direction specified as azimuth and inclination degrees (i.e. custom direction), with the associated header files (.sml, .hdr).

_VD

Vertical displacement values, with the associated header files (.sml, .hdr).

_disp

Slant Range (satellite view direction) displacement values, with the associated header files (.sml, .hdr).

_precision

Estimate of the data quality with the associated header files (.sml, .hdr). This file is generated only if the coherence file is entered as input.

_ALOS

Azimuth Line of Sight with the associated header files (.sml, .hdr). Positive angles are measured clockwise from the North; negative angles are measured counterclockwise from the North.

_ILOS

Incidence angle of the Line of Sight with the associated header files (.sml, .hdr). The angle is measured between the Line Of Sight and the vertical on the ellipsoid (flat earth).
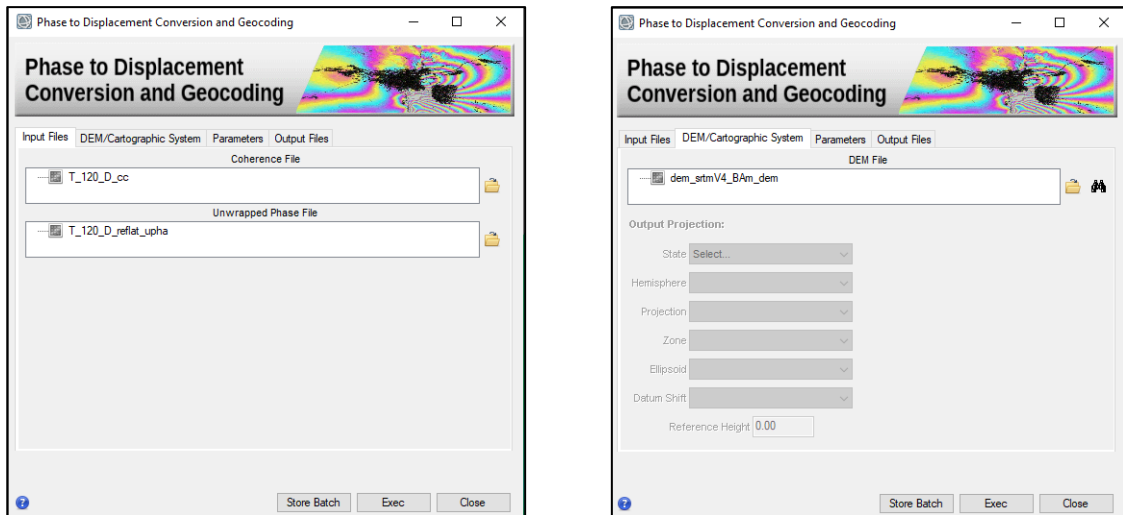
Figure 18 Phase to Displacement Conversion and Geocoding panels.

Figure 19 shows the displacement layer superimposed in transparency over the geocoded coherence layer. The central part of the interferogram shows the lowest values of coherence (darker areas), this corresponds to urban areas mostly affected by the quake.

Red and blue tones represent the areas of largest deformation (in opposite direction).
Greenish areas correspond to smaller deformation zones. The deformation field is calculated as generated from a N-S oriented strike-slip fault
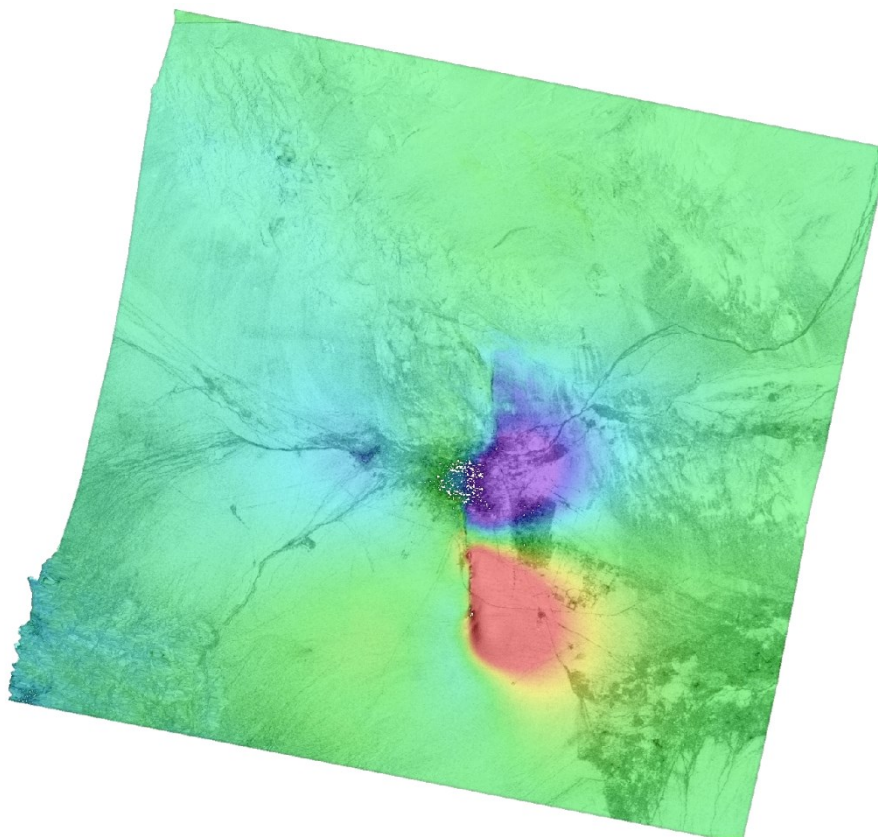
Figure 19 Geocoded displacement layer over the geocoded coherence image (_disp and _cc).

Result comparison - GACOS VS No GACOS

Here below is reported the comparison between two results, one where the atmospheric correction has been applied and the other one where the atmospheric correction has not been applied; the rest of the processing chain and the parameters used are the same.
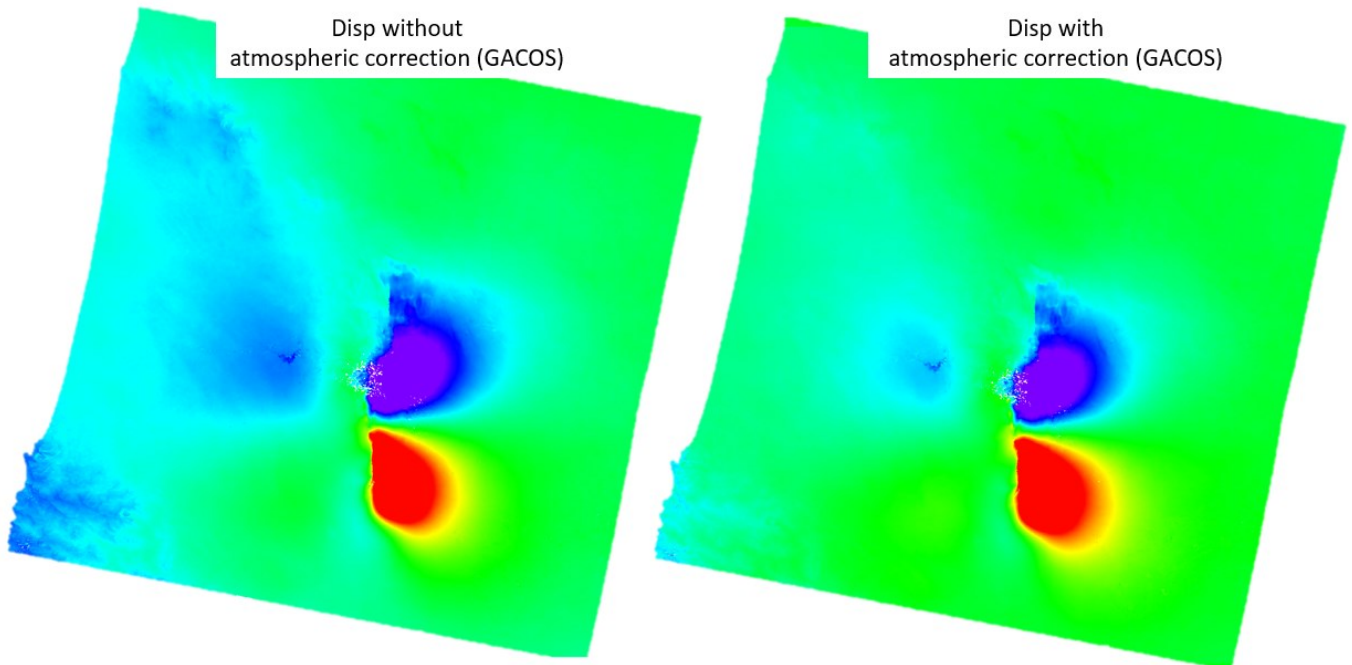

Figure 20 Comparison of the result with and without the application of the atmospheric correction.

On the bottom left side of the map on the left, is visible the presence of Residual phase correlated to the topography that is partially removed with the usage of GACOS data.

N.B: The evaluation of the results and the data interpretation is responsibility of the user.

11. DInSAR Dispalcement workflow

The operations described in the previous paragraphs can be executed in a single iteration through the DInSAR Dispalcement workflow tool (*Interferometry/DInSAR Displacement Workflow*); please note that the manual GCP creation is not allowed with the mentioned workflow.

This functionality enables to execute, in a single iteration, the following processing sequence:

- Import Generic SAR Data
- Interferogram Generation
- Adaptive Filter and Coherence Generation
- Phase Unwrapping
- Refinement and Re-flattening
- Phase to Displacement Conversion and Geocoding

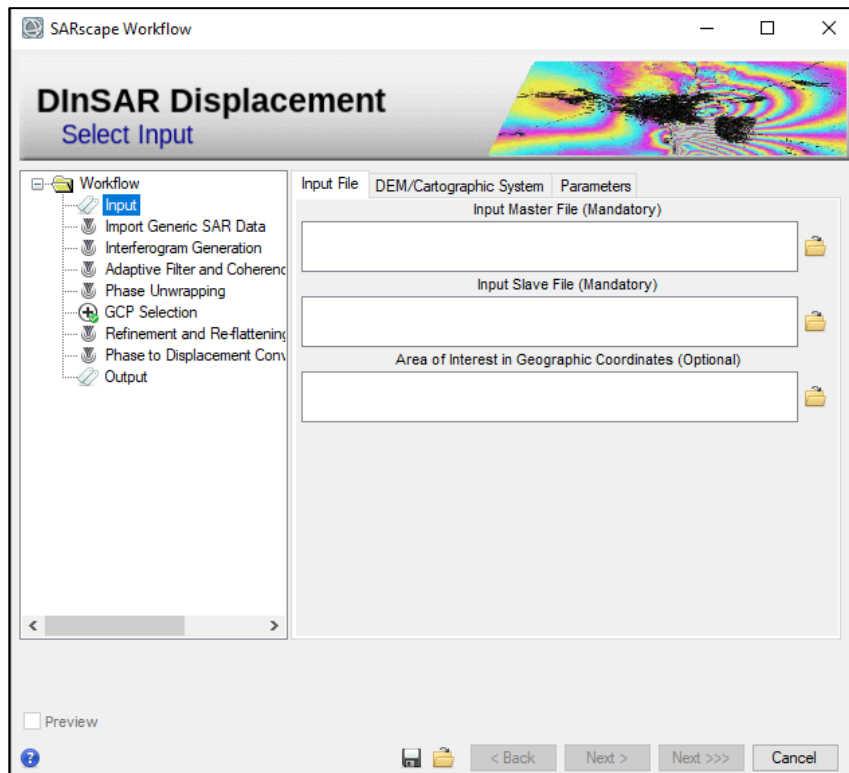The final purpose of this processing chain is the generation of a geocoded interferometric displacement map.

Figure 21 DInSAR Displacement workflow panel

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Annex 1. Filtering methods

Goldstein: The variable bandwidth of the filter, derived directly from the power spectrum of the fringes, smooths in a selective way the noise frequencies and the signal frequencies. In order to optimize the filter performance the "alpha" parameter, which characterizes the strength of the filter, is handled in an adaptive way on the basis of the local scene coherence: the lower the coherence the stronger the filter.

This filtering approach, which is an extension of the Goldstein method, significantly improves fringe visibility and reduces the noise introduced by temporal or baseline related decorrelation. In this implementation the alpha parameter is depending on the coherence: incoherent areas are filtered more than coherent zones. This implies a signal loss minimization, while strongly reducing the level of noise. The use of the coherence generated from the filtered interferogram (option enabled by setting the flag "Coherence from Fint"), must be carefully considered since the phase smoothing, which is produced by the filter itself, causes an over estimation of the coherence (the stronger the filter the higher the coherence values). If the objective is either not to unwrap areas which appear coherent but are actually very noisy or to use of the coherence data for other purposes (i.e. land cover classification or other qualitative/quantitative applications), the coherence shall be generated from the unfiltered interferogram or using the boxcar filtering approach.

Adaptive Non Local InSAR: In order to precisely estimate the coherence and filtering interferograms, a non-local filter, specifically designed for InSAR has been developed. This filter is based on the interferometric phase and amplitude similarity between the reference and secondary image in order to filter together pixels relevant to the same ground target, to avoid to mix the contribution of different scatterers.

This kernel used to measure the similarity is adaptive to overcome local distortions caused by strong backscattering variations (the so called "rare patches"), typical of the original filter design.
This algorithm implementation considers systematic phase ramp inside the similarity windows (estimated via FFT and removed before the process) to improve the similarity estimation itself and provide a better estimation of the underlying uncoherent phase noise. Moreover, this algorithm overcome the extra smoothing over strong amplitude variations areas between Reference and Secondary acquisitions, typical of the original implementation, exploiting an innovative Central Pixel Modulation based on the previous coherence estimated value.
The number of iterations for the weighted denoising is set to 3 by default.

Non-local-based filtering is an intrinsically, computationally demanding feature, due to its many comparisons between different image areas. Therefore, this tool put the underlying hardware components under stress and requires a significant amount of time. For this reason, our implementation is entirely written in OpenCL to take advantage of the massive level of parallelization offered by modern graphical processing units. Hence, we warmly recommended to use this filter only in combination with a powerful GPU selected as the current OpenCL platform/device under the SARscape Common Preferences. It is always possible to select and rely to a CPU-only OpenCL platform/device, but in such a case performance will roughly be one order of magnitude lower than using a modern GPU.

The results of this tool are the following products:
- Filtered interferogram
- Coherence
- Reference filtered power
- Secondary filtered power

The strength points of this filter with respect to the other filters are the following:
- details preservation in the filtered interferogram, in the coherence and in the power layers, vs homogeneous area stronger filtering
- unbiased coherence estimation (evident mostly in low coherent areas) due to the large processing window size.
- spatial resolution preservation for all the output layers (coherence included) with respect to input resolution; moreover, the spatial resolution is the same for all the derived products differently from the other coherence estimators.
- The coherence is estimated directly from the input differential interferograms and not from the filtered one. For this reason, the coherence can be used for quantitative measurements for land use monitoring.

Annex 2. Unwrapping methods

Minimum Cost Flow: It is the default unwrapping method to compute interferometry, from a pair of SAR images; this works over areas characterized by the presence of large areas of low coherence or other spatial recursive growing limiting factors; in such cases the Minimum Cost Flow algorithm enables to obtain better results than using the Region Growing method. This approach considers a square grid all over the image pixels. All pixels whose coherence is lower than the "Unwrapping Coherence Threshold" are masked out.

Delaunay MCF: It is the same approach of the previous method, with the only difference that the grid does not necessarily covers all image pixels, but only those above the "Unwrapping Coherence Threshold"; moreover it adopts the Delaunay triangular grid instead of square one. As result only the points with good coherence are unwrapped, without any influence from the low coherence pixels. The exploitation of the Delaunay triangulation is especially useful when there are several areas of low coherence (water bodies, densely vegetated areas, etc.) distributed throughout the image; in such case the others unwrapping approaches would eventually produce phase islands/jumps, while the Delaunay approach is able to minimize these jumps.

Region Growing: If this method is selected, it is suggested to avoid setting a high coherence threshold (good values are typically between 0.15 and 0.2) in order to leave enough freedom during the growing process; this shall limit the possibility to introduce erroneous phase jumps - "unwrapping islands" - in the output unwrapped phase image.

Decomposition Level

Another important factor is the Decomposition level (DCL). The process is normally executed with the original pixel sampling (i.e. 0) or with the minimum decomposition level (i.e. 1). The use of the decomposition is intended to multilook and undersample the data in an iterative way: the interferogram is unwrapped at the lower resolution and then reconstructed back at the original resolution.

The use of the decomposition can help to reduce unwrapping errors (e.g. in case of distributed low coherence areas) and it reduces the processing time and it limits the use of computer resources.

The user can specify the number of iterations (decompositions) to be executed; each iteration corresponds to an undersampling factor of 3. We suggest to avoid setting this value higher than 2. In case of very large displacements or very steep topography (fast phase/dense fringe distribution) the use of the decomposition can cause aliasing effects. In this case the decomposition process should be avoided by setting its value to 0.
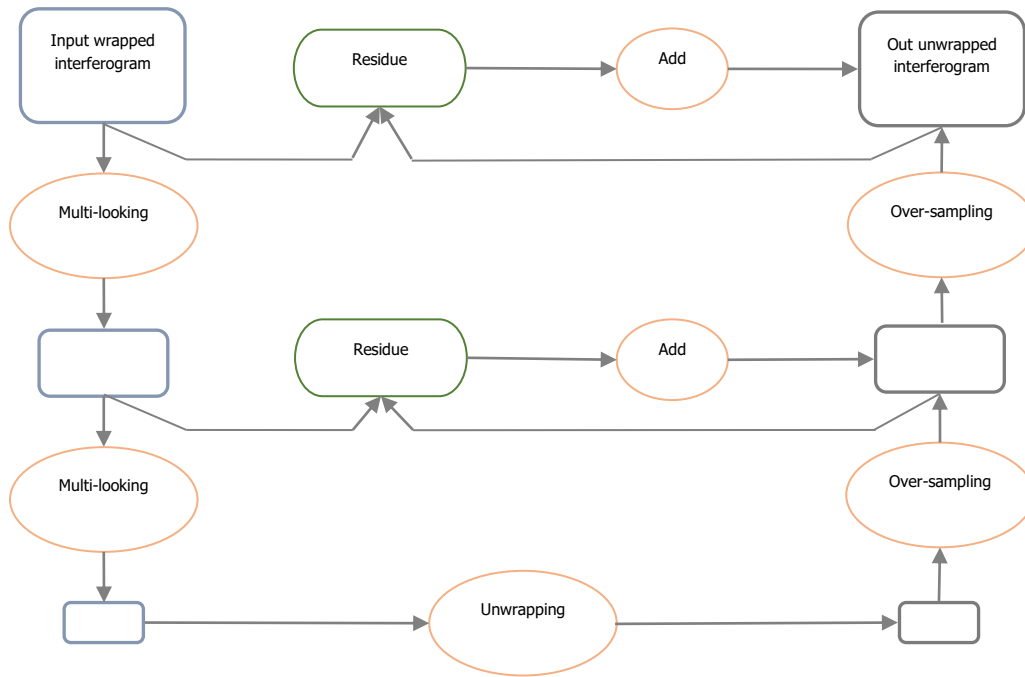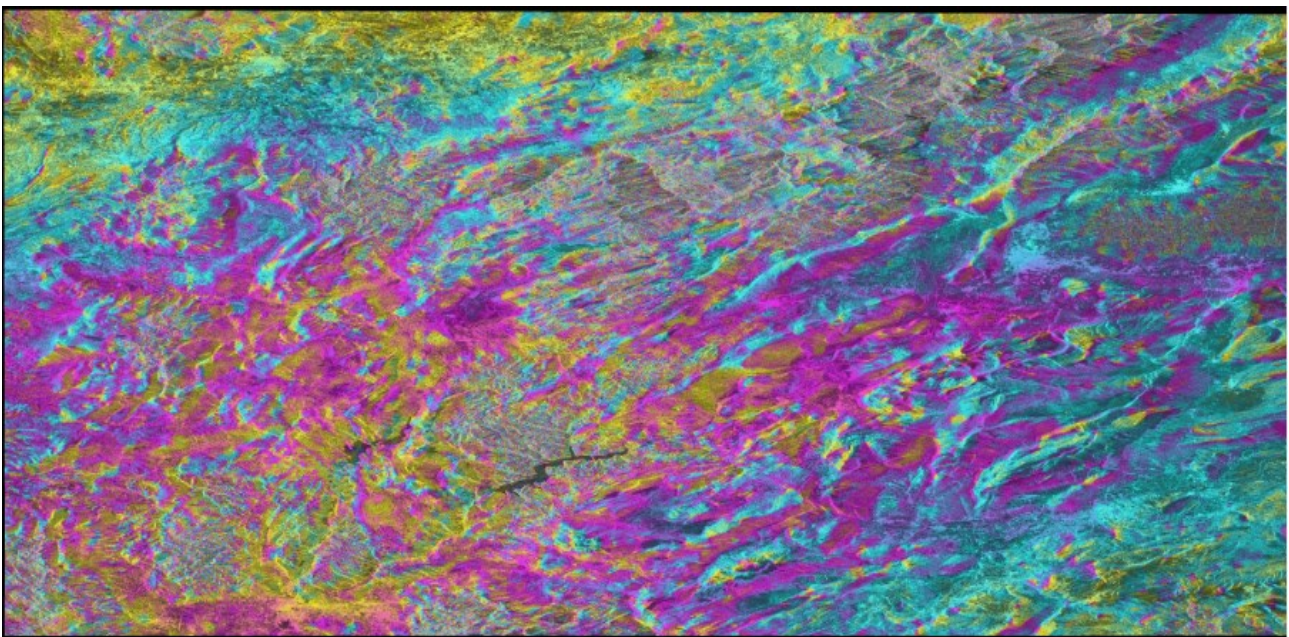
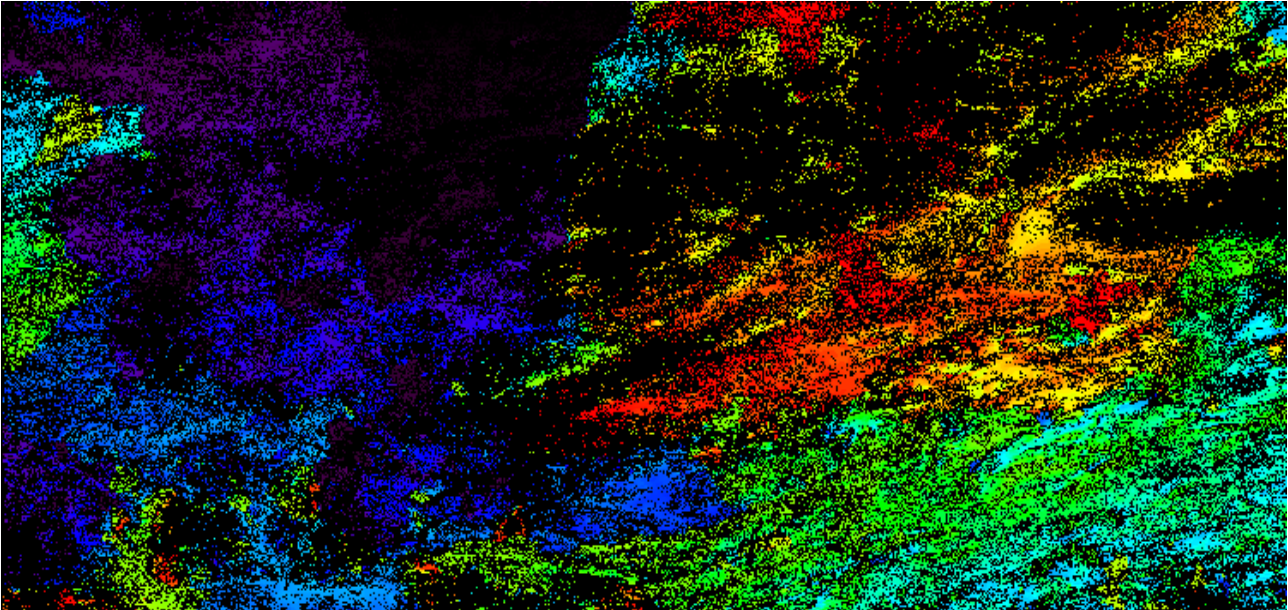Figure 22 Decomposition Level 2. The under-sampling is performed at each step with a multi-looking 3X3

Figure 23 Unwrapping with Delaunay MCF with and Decomposition level 1. Macroscopic phase jumps are visible.
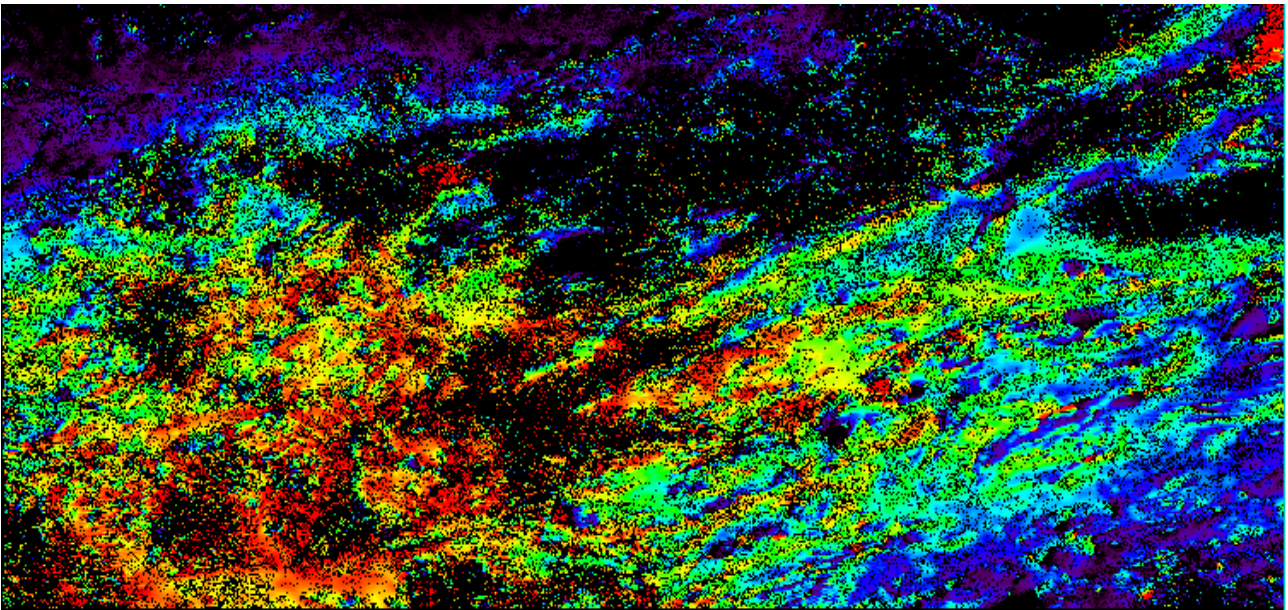

Figure 24 Unwrapping with Delaunay MCF and Decomposition level 2 has been used. The macroscopic phase jumps disappeared.

Be careful when increasing the Decomposition level number; macroscopically the improvement is meaningful and it significantly speeds up the software, but it can create localized discontinuities where the fringes to be unwrapped are too fast. The higher is the decomposition, the higher the probability to have aliasing problems.
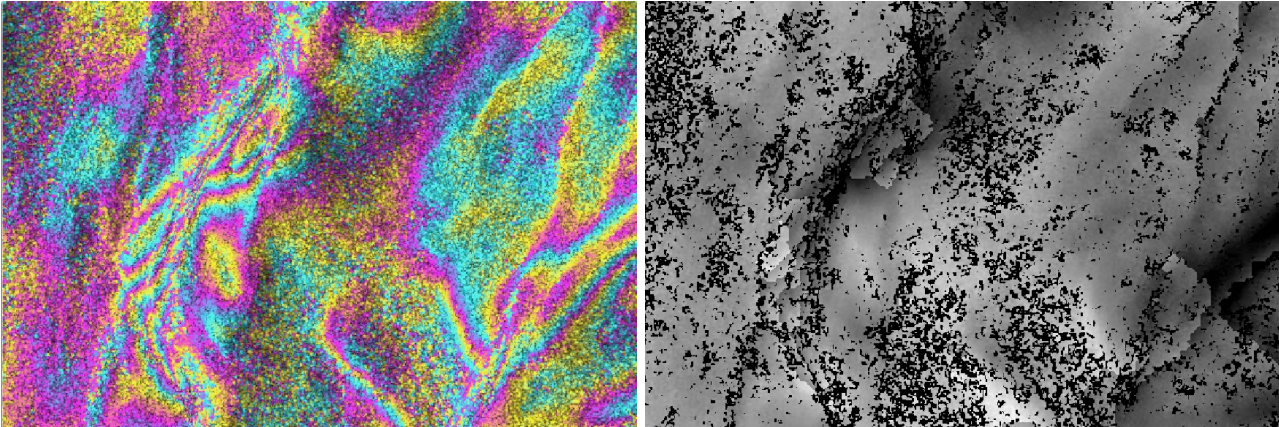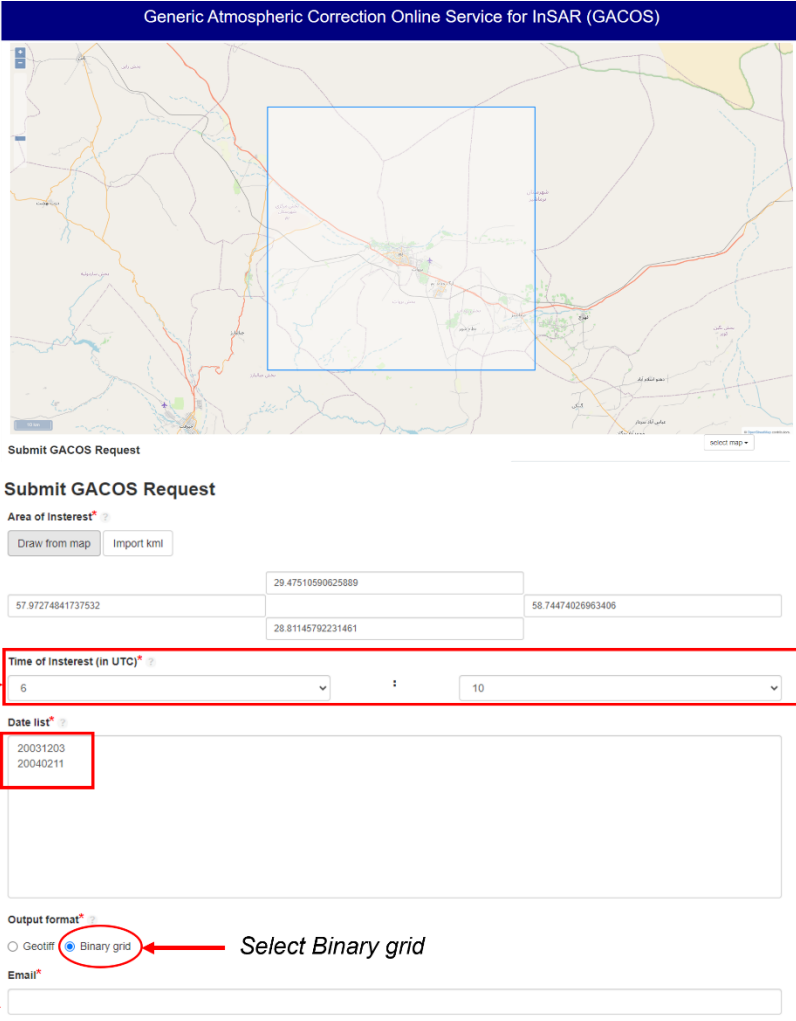
Figure 25 Zoom of the original (on the left) and unwrapped phase (on the right), obtained with Decomposition level 2. Many localized phase discontinuities appear where the fringes are too "fast" in the original interferogram.

Annex 3. GACOS Data Usage

GACOS utilizes the Iterative Tropospheric Decomposition (ITD) model (Yu et al., 2017) to separate stratified and turbulent signals from tropospheric total delays, and generate high spatial resolution zenith total delay maps to be used for correcting InSAR measurements and other applications. More details on GACOS data can be found at the following link: http://www.gacos.net/ GACOS data allows the improvement of the atmospheric correction within the interferometric processing.

The workflow for atmosphere removal through GACOS is the following:

- GACOS data have to be downloaded manually from the following website: http://www.gacos.net/, one GACOS data for each SAR image. Select the dates and time corresponding to the SAR image pair:

Figure 26 GACOS website.

- Then this data need to be imported in SARscape through the tool *Import Data/Other Format/GACOS,* at this stage the ztd_geo file are created.
- Open the tool *Interferometry/Interferometric Tools/Atmospheric Phase Delay Correction* and insert the GACOS ztd_geo files within the Optional Files panel. It is also necessary to set the *Atmosphere External*

Sensors within the Parameters panel (Figure 7). The tool will remove the atmosphere artefacts from the input file (_dint).

Input files

Interferogram file
File name of the previously generated interferogram (_dint or _fint). This file is mandatory.

Load the previously created _dint file.

Slant Range Digital Elevation Model file
Name of the Digital Elevation Model in slant range geometry (_srdem). This file is mandatory.

Optional Files

Optional Master Water Vapour File
File name of the master water vapour data or data file list (_filename_list.txt; *_bil). This file is mandatory only when the MERIS or GACOS sensor type is used.

Load the 20031203_ztd_geo file.

Optional Slave Water Vapour File
File name of the slave water vapour data or data file list (_filename_list.txt; *_bil). This file is mandatory only when the MERIS or GACOS sensor type is used.

Load the 20040211_ztd_geo file.

Unwrapped Phase File
Name of the unwrapped phase (_upha). This file is mandatory only when the Atmosphere Height Correlation Flag is selected.

Leave this field empty.

DEM/Cartographic System
Principal Parameters

Atmosphere External Sensors
By inserting this optional list, the software removes the atmosphere artefacts from the filtered interferogram stack using external sensors such as GACOS and MERIS (only for ENVISAT data).

Select GACOS.

Atmosphere Height Correlation Flag
By selecting this flag, the algorithm estimates and removes the height-related component of the atmosphere from each interferogram, using a the "Height Correlation Window Size [m]" (Atmosphere section) parameter to define the size of the filter. To enable this flag is mandatory to upload an _upha file within the Unwrapped Phase File filed.

Output

The output folder contains the following products:

Output Root Name
Name of the output root. This file is mandatory.

_corr_dint/fint

Corrected interferogram with the associated header files (.sml, .hdr).

_corr_mask

MERIS masked master and slave data, in the original image geometry, with the associated header files (.sml, .hdr).

_corr_atm

Atmospheric phase delay, in slant range SAR master image geometry, with the associated header files (.sml, .hdr).
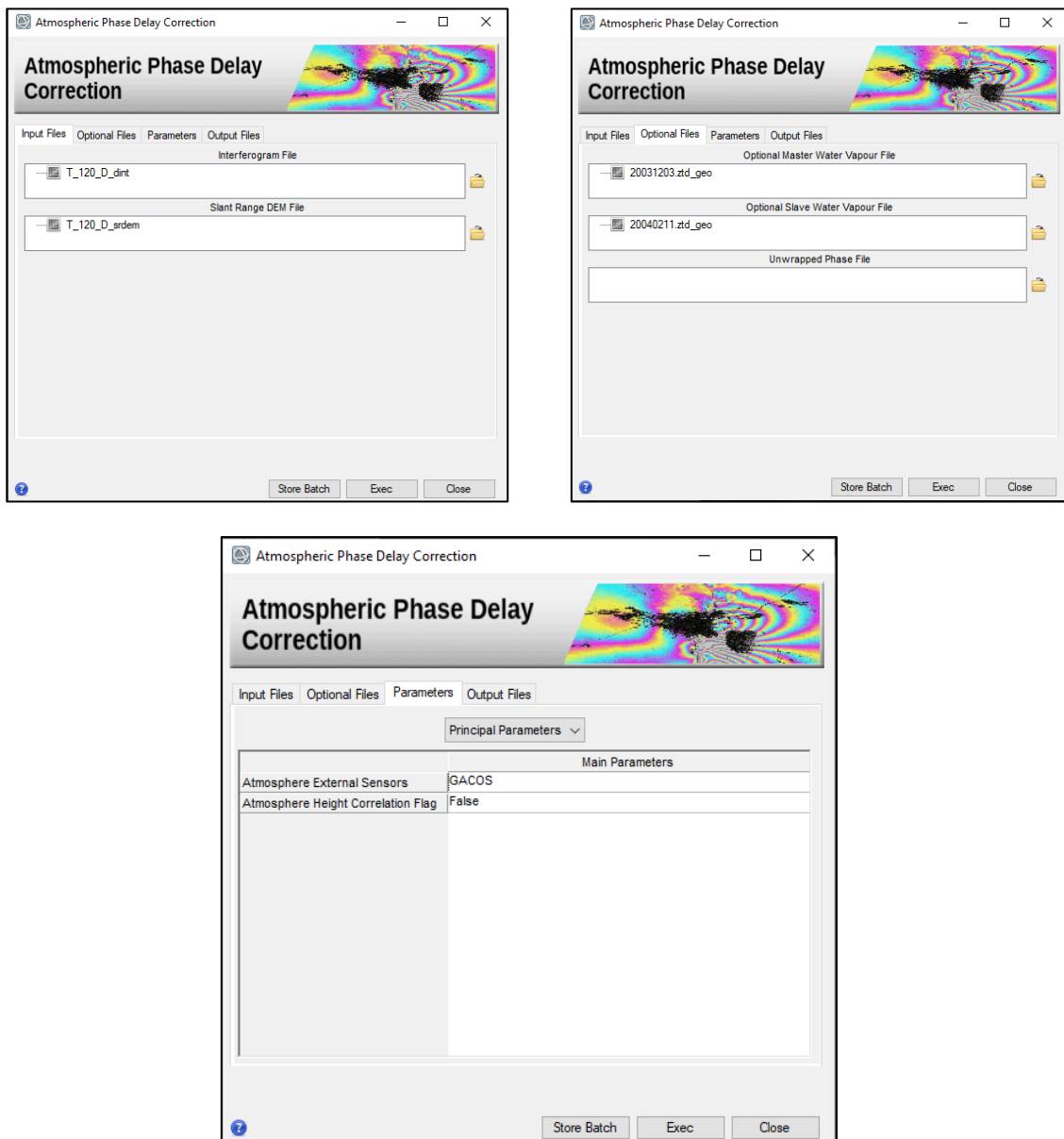

Figure 27 *Atmospheric Phase Delay Correction* panels.

The corrected flattened interferogram has a lower number of fringes compared to the flattened interferogram, the correction acts especially on the low-frequency fringes, visible in the upper-right and left side of image (Figure 7).
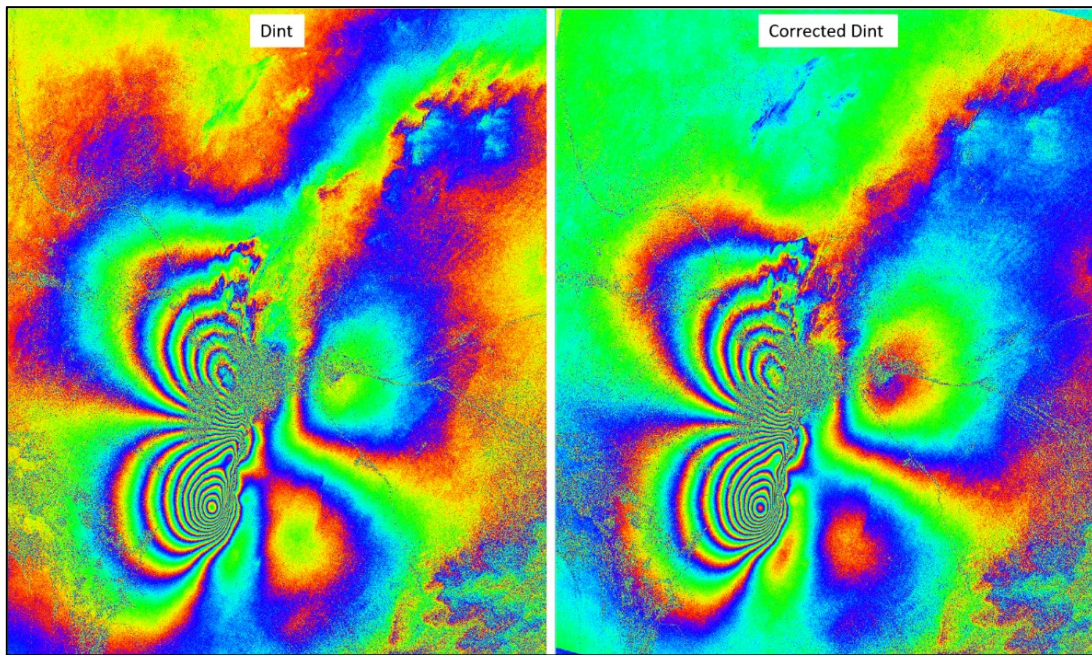
Figure 28 Flattened interferogram (_dint), on the left, vs atmosphere corrected and flattened interferogram (_dint_corr), on the right.