

Enhanced-SBAS Tutorial

SARscape Version 6.1.0

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1. Introduction

The main goal of this tutorial is to give a basic description of the SARscape SBAS and E-SBAS processing chain to obtain **precise topography, average displacement models** and **displacement time series** that allows the monitoring of the temporal evolution of surface deformations affecting distributed targets.

The new **E-SBAS** technique identifies and process Permanent Scatterers pixels together with Distributed Scatterers ones. Providing a more comprehensive and valuable output. E-SBAS is capable of measuring Non-Linear displacement trend to both PS and DS pixels.

The proposed approach for E-SBAS is inspired by (Lanari, 2004). The deformation products will be obtained exploiting a combination of both Small Baseline subset (SBAS) and Persistent Scatterers Interferometry (PSI) methods, in order to estimate the temporal deformation at both DS and point-like PS. The low-pass (LP) and high-pass (HP) terms are used to name the low spatial resolution and residual high spatial frequency components of signals related to both deformation and topography.

The role of the SBAS technique is twofold: on the one hand, it will provide the LP deformation time series in correspondence of DS points and the LP DEM-residual topography; on the other hand, the SBAS will estimate the residual atmospheric phase delay still affecting the interferometric data after the preliminary correction carried out by leveraging GACOS products and ionospheric propagation models.

The temporal displacement associated to PS points will be obtained applying the PSI method to interferograms previously calibrated removing the LP topography, deformation and residual atmosphere estimated by the SBAS technique. This strategy "connects" the PSI and SBAS methods ensuring consistency of deformation results obtained at point-like and DS targets and, therefore, provides better results with respect to the approach of executing the two methods independently from each other. The proposed hybrid approach is not just the simple application of the two techniques independently, indeed, the proposed approach is able to analyze both strong reflectors and distributed targets, delivering lower resolution DS results combined with higher resolution PS for even non-linear trends in an integrated continuous spatial solution.

As reminder, the SBAS approach is based on the Differential Interferometric Synthetic Aperture Radar (DInSAR) technique, which refers to the basic principles of the interferometry. The interferometric phase is the contribution of 4 components: the topographic component, the phase noise component, the displacement component, and the atmosphere component. A stack of images allows the separation of the different components.

The E-SBAS approach can achieve a precision of about 1-2 mm/year for temporal and spatial coherent areas, comparable with GPS and Persistent Scatterers PS measurements. The measured precision decreases where temporal and spatial coherence decrease, as for instance over vegetated or snowed areas.

Note: To run an E-SBAS processing it is necessary to compute an SBAS processing until the Second Inversion Step, see the E-SBAS block diagram reported in Figure 1.

Workflow Overview

The E-SBAS technique uses the input SLC data to select the pair combinations for the interferogram generation. The Super Master is automatically chosen among the input acquisitions. The Super Master is the reference image of the whole process, and all the slant range pairs (specified in the *CG_report.txt*) are **co-registered** on this slant range reference. Once the co-registration is performed, the **interferograms** are generated. Using a reference Digital Elevation Model (DEM) the **flat earth** and the **topography** are **removed**. The better the reference Digital Elevation Model accuracy/resolution the better the result in terms of topography removal and quality of co-registration. To **remove the phase noise**, the flattened interferograms are filtered. Starting from the **filtered interferograms**, the **spatial coherence** is calculated for each interferogram. 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 SBAS steps require a **refinement and re-flattening** process before proceeding to remove the offsets and the trends from the stack of unwrapped phases (Inversion step) or from the final products (Geocoding step).

The re-flattened unwrapped phases are used by both SBAS Inversion steps for the **estimation of the modeled displacement rate and of the topographic residuals** with respect to the reference DEM. The E-SBAS processing, is capable to estimate linear and non-linear displacement trends, applied for both DS and PS pixels.

Once the date by date displacement measurements (known as high pass components) are carried out, the algorithm performs the **estimate of the atmospheric effects**. First, the displacement model previously estimated is subtracted date by date, from the interferograms measurements (*_dint* files). Then the atmospheric correction is performed through the application of an **Atmosphere Low Pass filter (LP)**, this accounts for the spatial distribution of the atmospheric variations. It is implemented by using a square window: large windows are more suitable to correct large scale variations, while small windows are better to correct isolated artifacts due to localized variations. **The smaller is the window size, stronger will be the filter effect.**

Once the atmosphere and the LP component phase trend are removed, the algorithm estimates the temporal coherence for each pixel, providing the linear residual-velocity that best fits the temporal evolution of the residual-phase measurements for that point. As mentioned, the LP components are estimated by SBAS processing instead of the first PS inversion which can only estimate a linear trend. The residual-phase measurements is obtained by removing the LP phase components and the atmosphere. The **PS High Pass (HP)** algorithm is then applied on the residual phase.

The PS processing is applied to each pixel, and if the coherence value is higher than the threshold configured by the user, the point is treated as a PS (the previous velocity is added back to the residual-velocity estimated by the PS matching and the time series is defined via temporal unwrapping), otherwise it remains a DS (with velocity and time series derived from SBAS) or it is rejected (if it is not even a DS).

The displacement values are reported with:

- Positive sign if the movement corresponds to a decrease of the sensor-to-target slant range distance.
- Negative sign if the movement corresponds to an increase of the sensor-to-target slant range distance.

It is worthwhile to mention that the re-flattening, which is performed on the displacement products, does not foresee the orbital refinement; it means than only a ramp (using minimum three GCPs) or a constant term (using minimum one GCP) can be removed.

The E-SBAS performed steps and sub-steps are described in the list below and correspond to the logical workflow shown in Figure 2:

SBAS Processing Chain

1. Connection Graph
2. Interferometric Workflow
 - 2.1. Co-registration
 - 2.2. Differential interferogram generation
 - 2.3. First Phase Unwrapping: standard 2D
3. Inversion First Step
 - 3.1. Unwrapped phase stack Refinement and Re-Flattening
 - 3.2. Average displacement model and residual topography estimation
 - 3.3. Second Phase Unwrapping: standard 2D
4. Inversion Second Step
 - 4.1. Unwrapped phase stack Refinement and Re-flattening
 - 4.2. Displacement low pass (LP) component estimation
 - 4.3. Atmosphere pattern removal
 - 4.4. Mean power image and precision component estimation
 - 4.5. Temporal coherence and other ancillary information estimation
5. Geocoding (*not mandatory for E-SBAS processing*)
 - 5.1. Final product Refinement and Re-Flattening
 - 5.2. Average displacement model, precisions, and other layers geocoding in shape and raster format
 - 5.3. Displacement time series geocoding in shape and raster format

E-SBAS Processing Chain

1. Connection Graph
2. Interferometric Workflow
 - 2.1. Co-registration
 - 2.2. Differential interferogram generation
3. Inversion
 - 3.1. Low pass component subtraction from differential interferogram
 - 3.2. Atmosphere estimation and removal
 - 3.3. Displacement high pass (HP) component estimation
 - 3.4. Integration of LP and HP displacement component
4. Geocoding
 - 4.1. Final product Refinement and Re-Flattening
 - 4.2. Average displacement model, precisions, and other layers geocoding in shape and raster format
 - 4.3. Displacement time series geocoding in shape and raster format

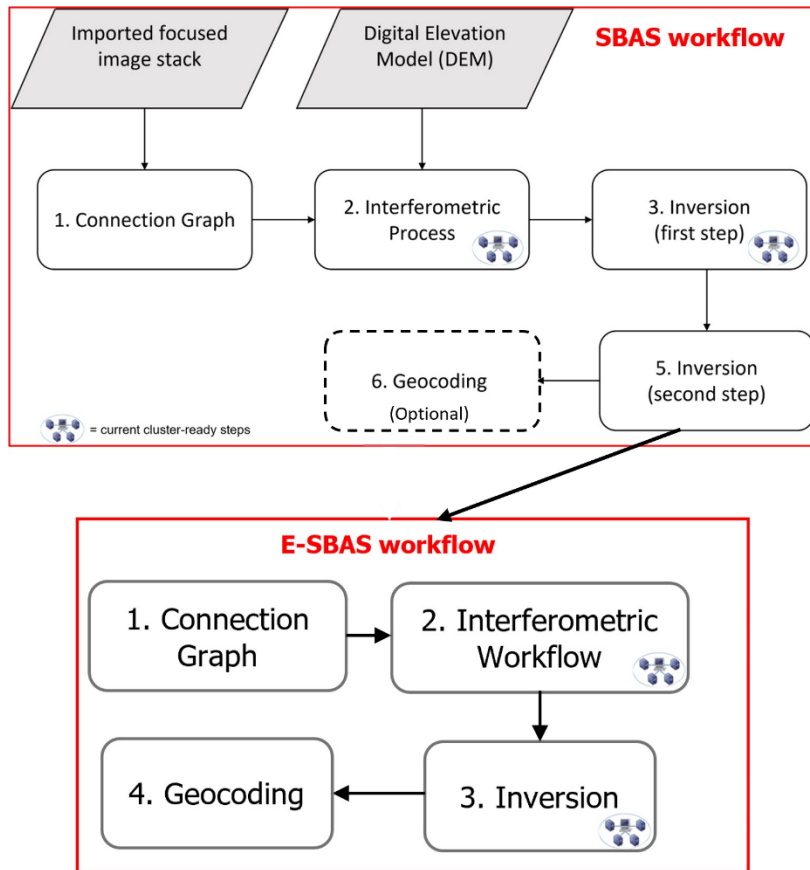


Figure 1 E-SBAS block diagram

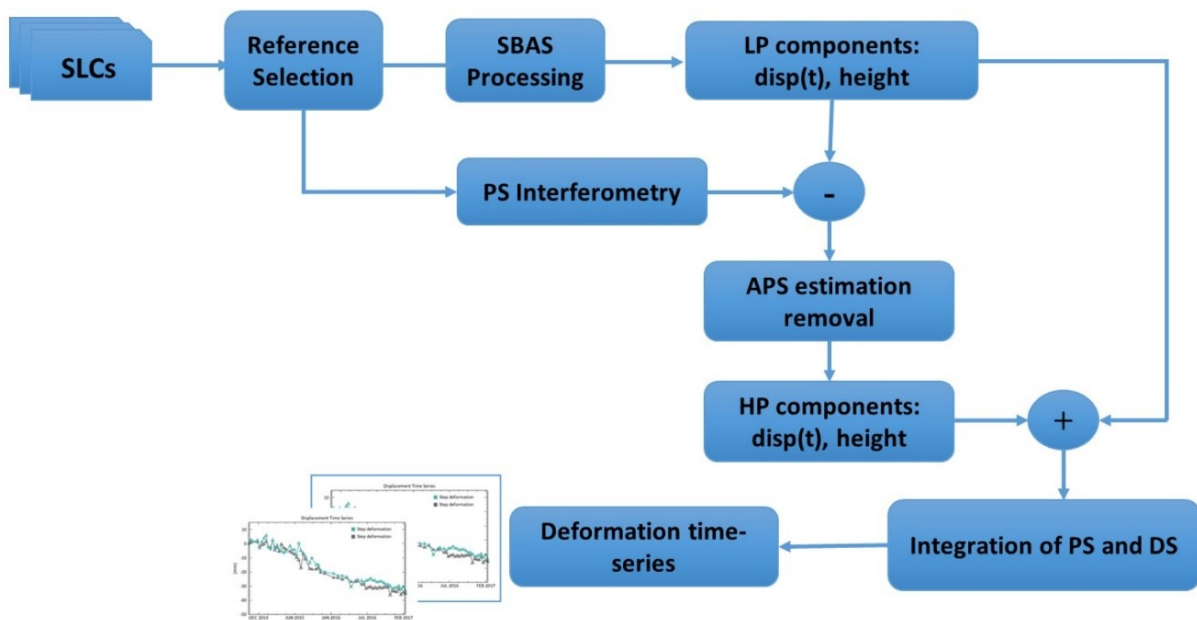


Figure 2 E-SBAS logical workflow

The SBAS and E-SBAS processing described in this tutorial was performed in a workstation with the following characteristics:

SARscape version	6.1.0
ENVI version	6.0.0
SO	64-bit Windows 10 Pro
RAM	32 GB
Processor	Processor AMD EPYC 7313 16-Core Processor, 3001 Mhz, 16 Core(s), 32 Logical Processor(s)
OpenCL	AMD EPYC 7313 16-Core Processor
HD	SSD (as working directory)

The entire sample data stack and the SBAS/E-SBAS results shown in this tutorial can be found in the DataSetsTutorials folder on our FTP ([ftp.sarmap.ch](ftp://ftp.sarmap.ch)). Please contact us at support@sarmap.ch to get the login credentials to access the FTP providing the full name of the license owner, the name of your institution and the license number.

2. Training Data sets description

The training dataset concerns the tailings dam collapse occurred at the Cadia Gold Mine on March 9th 2018. The mine is operated by Newcrest Mining, in Orange, New South Wales, Australia. Cadia is one of the largest open cur gold and copper mines in Australia.

The collapse appears to have occurred on the Northern Tailings Storage Facility, on a dam that links two tailings storage areas. The tailings were captured within the basin of the STSF. *“There were no injuries or loss of life, primarily due to a perceptive and timely evacuation of the site prior to the Event in accordance with the CVO Dam Safety Emergency Plan (source Newcrest)”*:



Figure 3 The tailings dam failure at Cadia mine in Australia. Image from Newcrest.

The AOI is covered by Sentinel-1 track number 45, Descending orbit. A datastack of 85 images in VV polarization will be used, the temporal coverage is from March 2015 to April 2018.

To obtain the 2D displacement projected along the vertical and east-west direction The E-SBAS technique has to be applied separately to each geometry, performing all the steps from the Connection graph to the Geocoding in order to obtain a consistent result.

In this tutorial only the Descending dataset processing is described, therefore the images and graphs correspond to the track 45.



3. Figure 4 Cadia AOI.

3. Processing Time

The Table below summarizes the processing time to perform the E-SBAS in the Cadia area for the Descending dataset. The processing time reported considers only the computational time and it represents only a rough estimate by considering a machine with moderate performance. The operator time required to analyze each step results is not reported since it depends on the user knowledge and experience in E-SBAS processing.

SBAS Processing chain	
Dataset	45D (85 acquisitions)
Step	Time [hh:min:ss]
Connection Graph	00:01:00

Interferometric Process	01:15:00
Inversion: First Step	00:20:26
Inversion: Second Step	00:05:00
Geocoding	00:02:01
E-SBAS Processing chain	
Step	Time [hh:min:ss]
Connection Graph	00:01:00
Interferometric Process	00:13:00
Inversion	00:02:34
00:01:00	00:01:00

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 Sentinel-1 TOPSAR (IW – EW).
- 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 SBAS 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 E-SBAS technique users have to consider suitable sensors and acquisition modes, as well as small temporal and/or spatial separation (baseline) between the acquisition orbits. The provided dataset is suitable for E-SBAS processing.

TIP This tutorial performs the E-SBAS processing in a defined area of interest. If users want to analyze a different dataset, they should consider that a full frame processing is fully discourage if they do not have the E-SBAS cluster version because of the dramatic computational resources needed. To reduce the processing time a sampled dataset is strongly recommended.

To quickly analyze the results of each step, SARscape stores each output in the corresponding folders. In fact, once the *Connection Graph* step is performed, the "Output Root Name"_SBAS_processing and the _ESBAS_processing folders are created.

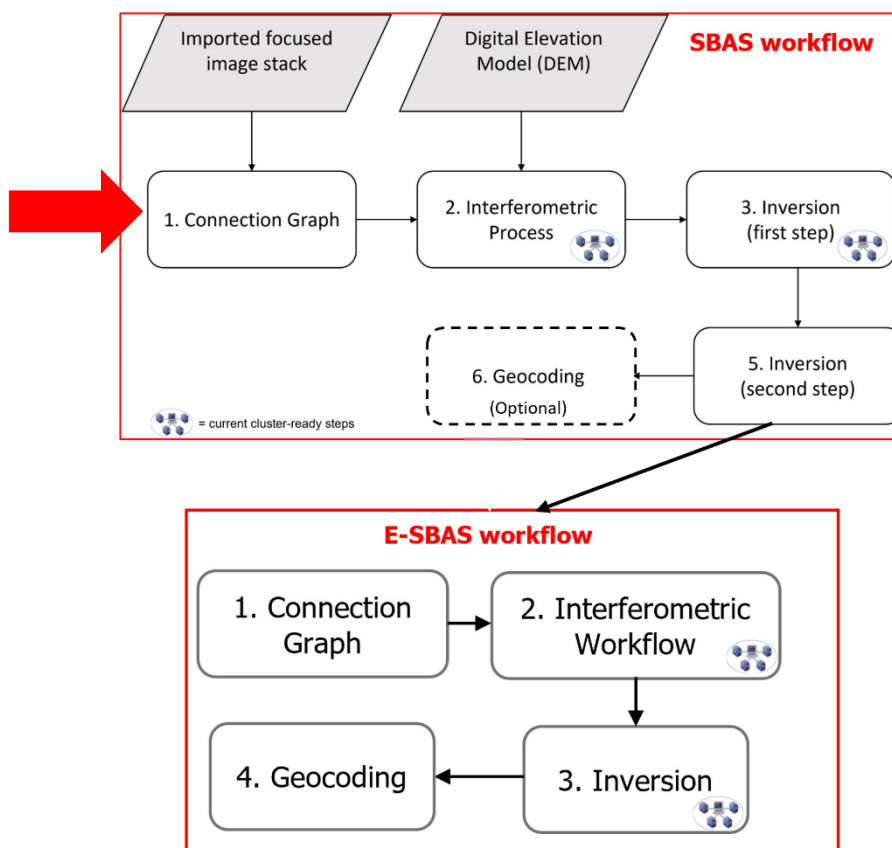
The principal sub-folders relevant to the E-SBAS processing chain are:

- connection_graph
- interferogram_stacking
- inversion
- work.

Note that all the parameters that need to be set or changed by the operator, different from the default values, are highlighted in this document using orange color of the text.

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.

5. SBAS - Connection Graph Generation



This functionality defines the SAR pair combination (Masters and Slaves) and the connection network, which is used for the generation of the multiple differential interferograms. This step is mandatory and deletes any content present in the output root folder if a process with the same root name has been performed before.

The pairs to be processed are shown as connections in a network that links each acquisition to the others. Given N acquisitions, the maximum theoretical possible connections, connecting each acquisition with all the others, are $(N*(N-1))/2$. For each pair, an interferogram is generated in the *Interferometric Process* step.

TIP The connection graph can be edited using the specific tool in */SARscape/Interferometric Stacking/SBAS & E-SBAS/SBAS Tools/SBAS Edit Connection Graph* (see Annex 4). The editing can be performed before or after any SBAS steps.

The *Connection Graph* is performed running the */SARscape/Interferometric Stacking/SBAS & E-SBAS/1 - Connection Graph* panel (see Figure 5).

Input files

Insert all the *_slc* or *_slc_list* files, previously prepared, in the Input file list tab from the "45D_cut" folder of the dataset.

Optional file

Leave the Input Master file empty (this file is automatically chosen by SARscape).

Principal Parameters

Min Normal Baseline (%)

This threshold corresponds to the minimum percentage of the critical baseline value, which is considered acceptable in the generation of the possible data connections.

Max Normal Baseline (%)

This threshold corresponds to the maximum percentage of the critical baseline value, which is considered acceptable in the generation of the possible data connections.

Min Temporal Baseline (days)

This threshold corresponds to the minimum temporal distance, which is considered acceptable in the generation of the possible data connections. This value is expressed in days.

Max Temporal Baseline (days)

This threshold corresponds to the maximum temporal distance, which is considered acceptable in the generation of the possible data connections. This value is expressed in days.

Degree of Redundancy

A further degree of redundancy selection criteria can be specified:

- *high*, all the interferograms respecting the previous Baseline thresholds are accepted.
- *low*, the program tries to minimize the number of interferograms to be generated, based on the Graph Redundancy Criteria and on Min Connection per Acquisition

Redundancy Criteria

The following selection criteria are foreseen for the removal of redundant connections, when the Degree of Redundancy is *low*:

- *Min Normal Baseline*, the number of connections is minimized by keeping only those having the smallest spatial baseline.
- *Max Normal Baseline*, the number of connections is minimized by keeping only those having the largest spatial baseline.
- *Min Temporal Baseline*, the number of connections is minimized by keeping only those having the smallest temporal baseline.

Max connections per Acquisition

Number of connections (interferograms) per acquisition remaining after the redundancy reduction. This parameter indicates the average redundancy of the connection graph, and bibliography suggest setting a value higher than 5 to obtain reliable inversion solutions.

Allow Disconnected Blocks

The standard approach of SBAS requires a fully connected graph. If this is not possible, the SBAS can also work with temporal discontinuities and connect the time-series (blocks) before and after the discontinuities. Flagging the 'Allow Disconnected Blocks' option, the SBAS works on continuous groups of acquisitions and extrapolate the First Inversion model for the disconnected time intervals.

By setting this option to True, the program does not discard any group of images and the disconnected SBAS functionality is automatically activated for the next inversion steps.

The choices are the following:

- *False*: when the graph is not fully connected the disjointed acquisitions and blocks are rejected.
- *Allow*: the disjointed acquisition blocks are kept.

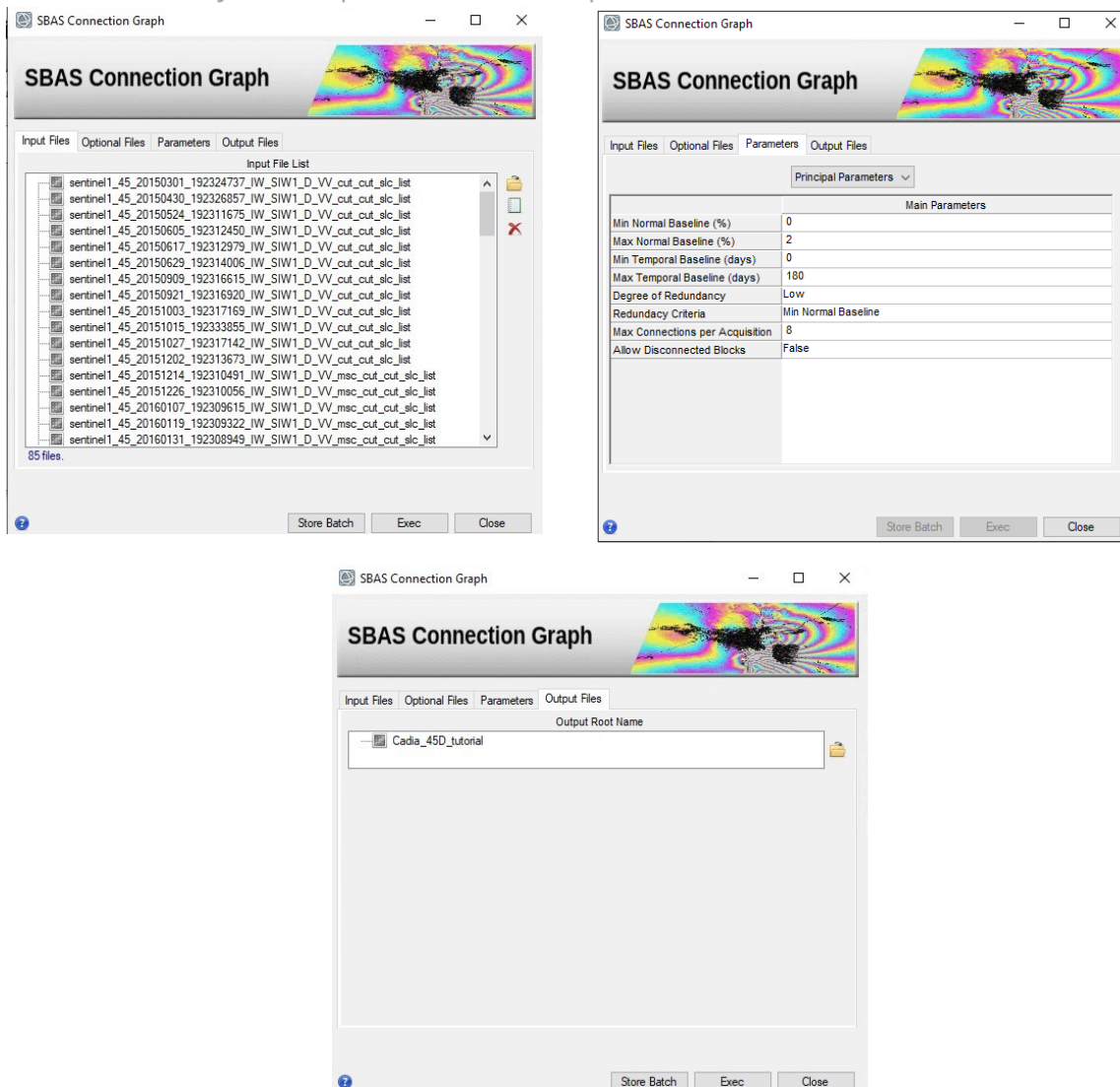


Figure 5 Connection Graph panels.

Output Files

Choose the location of the processing folder and an Output Root name.

The Output Root Name is used to create the processing folder. The folder name is given by the following composition: "Output Root Name"_SBAS_processing.

Once the SBAS Connection Graph process is completed, a report and two graphs are displayed (Figure 6). The graphs are:

- *Time-Position plot*, which provides the relative normal distance between the acquisitions in meters (y axis), and the input acquisition dates (x axis). The *Time-Position plot* allows users to visually understand if the graph is fully connected and matches with required redundancy criteria. The higher the connection the most reliable displacement estimates.

TIP The theoretical minimum average number of connections per acquisition is 5; we suggest an ideal configuration of 10 connections per acquisition. Obviously, as you increase the number of connections, the computational time is increasing.

- *Time-Baseline plot*, which provides the normal baseline in meters (y axis) and the input acquisition dates (x axis). This graph shows the interferogram coverage for each date.

Each acquisition is represented by a diamond. The color of the diamond symbol is as follows:

- Red: discarded acquisitions due to user specific constraints.
- Green: valid acquisitions.
- Yellow: Super-Master acquisition. The Super-Master is the reference image of the whole processing, and all the processed slant range pairs are co-registered and overlaid to this reference geometry.

TIP The graphs can be reloaded at any processing step from */SARscape/Interferometric Stacking/Stacking Tools/Plot Viewer* panel by adding the auxiliary file.

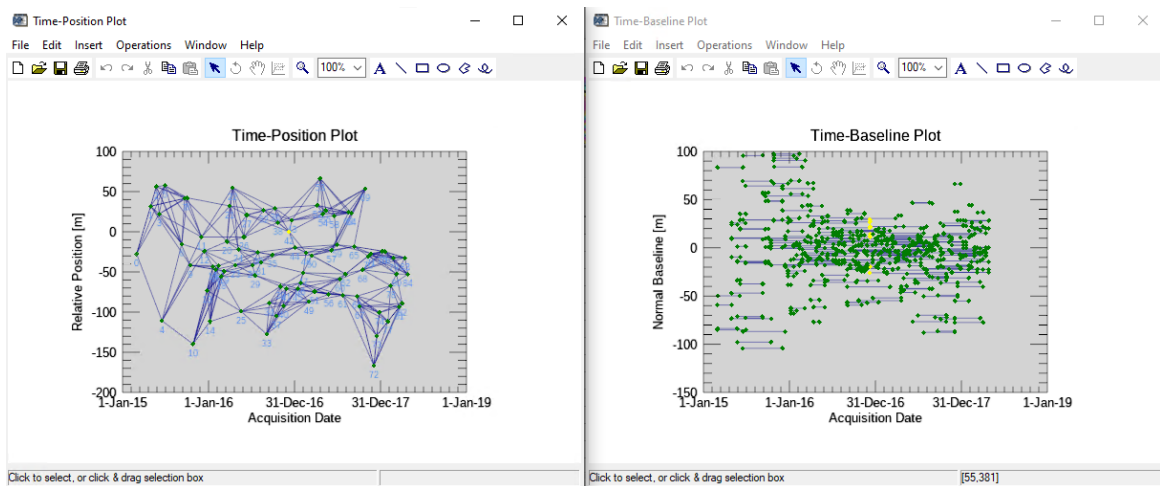


Figure 6 Plots generated by the *Connection Graph* tool.

In addition to the plots, the multi-looked Super-Master image (suffix, "_pwr") is also generated and displayed in ENVI (Figure 7). The multi-looked factor is automatically computed based on the grid size specified for the sensor once the *Preferences specific* are set.

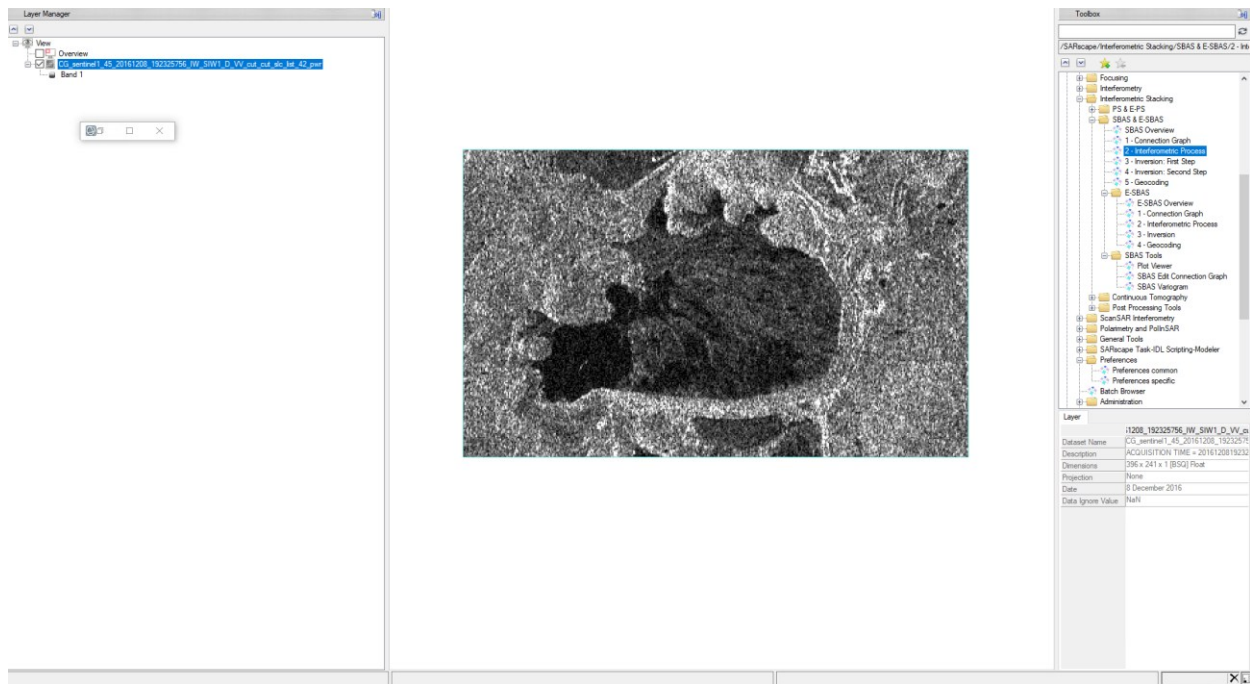


Figure 7 Multi-looked Super Master image.

The *Connection Graph* step generates the *auxiliary.smf* file, the connection graph folder results, and the work folder.

The auxiliary file is the principal file that guide users in the SBAS processing, all the mandatory SBAS steps are based on the auxiliary file (see Annex 1).

The Connection graph folder includes:

- *CG_report.txt*, which summarizes the graph pairs characteristic, such as the total number of interferograms that shall be generated by the *Interferometric Process* step and involved in the following steps. Given the actual stack of input acquisitions and constraints set, the number of interferograms shall be generated by *Interferometric Process* step are 276. With an average number of interferograms per acquisition equal to 9.4.
- *plot* sub-folder, which is used to store the files (*CG_baseline.txt* and *CG_position.txt*) necessary for the visualization of the graphs in ENVI.

The work folder includes sub-folders. The subfolders are created in the work folder once each step of the SBAS processing chain is run, and their name is automatically given by the step name.

It is worth to mention that the *parameters.smf* file is also created in the work folder. In this file all the set parameters used in that processing are recorded.

6. SBAS - Interferometric Process

The *Interferometric Process* step creates a stack of multi-looked unwrapped interferograms through a few sub-steps: *co-registration*, *differential interferogram generation*, optional *phase pattern removal* and *unwrapping*. The sub-steps implemented here are executed using the standard DInSAR processing approach.

The data multi-looking factors are referred to the Super Master image.

TIP We suggest processing the distributed targets with a looks number greater than 1 look (range looks x azimuth looks), to obtain wrapped interferograms with a higher Signal to Noise Ratio (SNR), capable to provide more reliable coherence estimates and continuous unwrapped phases.

The *Interferometric Process* is performed running the */SARscape/Interferometric Stacking/SBAS & E-SBAS/2 - Interferometric Process* panel (see Figure 8).

Input files

Insert the *auxiliary.sml* file.

Optional file

Leave the Geometry GCP File empty.

Leave Avoid Moving Area File empty.

Leave Optional Water Vapor List empty.

Leave Classification Mask File empty.

DEM/Cartographic System

Insert the *aw3d30_dem* provided in the dataset.

Principal Parameters

Rebuild All

By setting this flag the whole process is started from scratch. It is advisable to leave this flag unchecked in case of process interruption, so that the products already generated have not to be computed and stored again.

Range Looks

Number of looks in range referred to the Super Master.

Azimuth Looks

Number of looks in azimuth referred to the Super Master.

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.

Number of Parallel Unwrapping

Defines the number of unwraps that will be performed in parallel (one interferogram for each thread). This parameter must not exceed the total number of CPU threads. The user should consider the available system memory before increasing the number of parallel processes, as the memory consumption is directly related to the number of unwraps performed in parallel.

Apply Layover and Shadow Mask

Mask the results in layover and shadow areas.

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). The external layers must be previously downloaded and imported with the appropriate tools. The algorithm checks the correspondence between the SAR acquisition and the external sensor layer stack dates, before converting to the slant range Zenith Path Delay (ZPD) and removing it from the corresponding interferograms.

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. The smaller this window the more spatial (height-related) details will be removed from the interferograms. This flag is dedicated to mountainous areas with atmospheric artifacts strongly correlated to height.

Co-registration with DEM

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

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.

TIP At this step it is recommended to set decomposition level at 0 (expensive for the calculation times, but able to better preserve fast spatial phase variations) or 1 (faster, more robust with noisy interferograms, but in cases of very fast spatial phase variations may suffer from aliasing problems).

Unwrapping Coherence Threshold

Pixels with coherence values smaller than this threshold are not unwrapped and set to NaN.

Filtering method

The choice is given among the following filtering methods:

- *Boxcar window*.
- *Goldstein*.
- *Adaptive window*.
- *Adaptive Non-Local InSAR*.

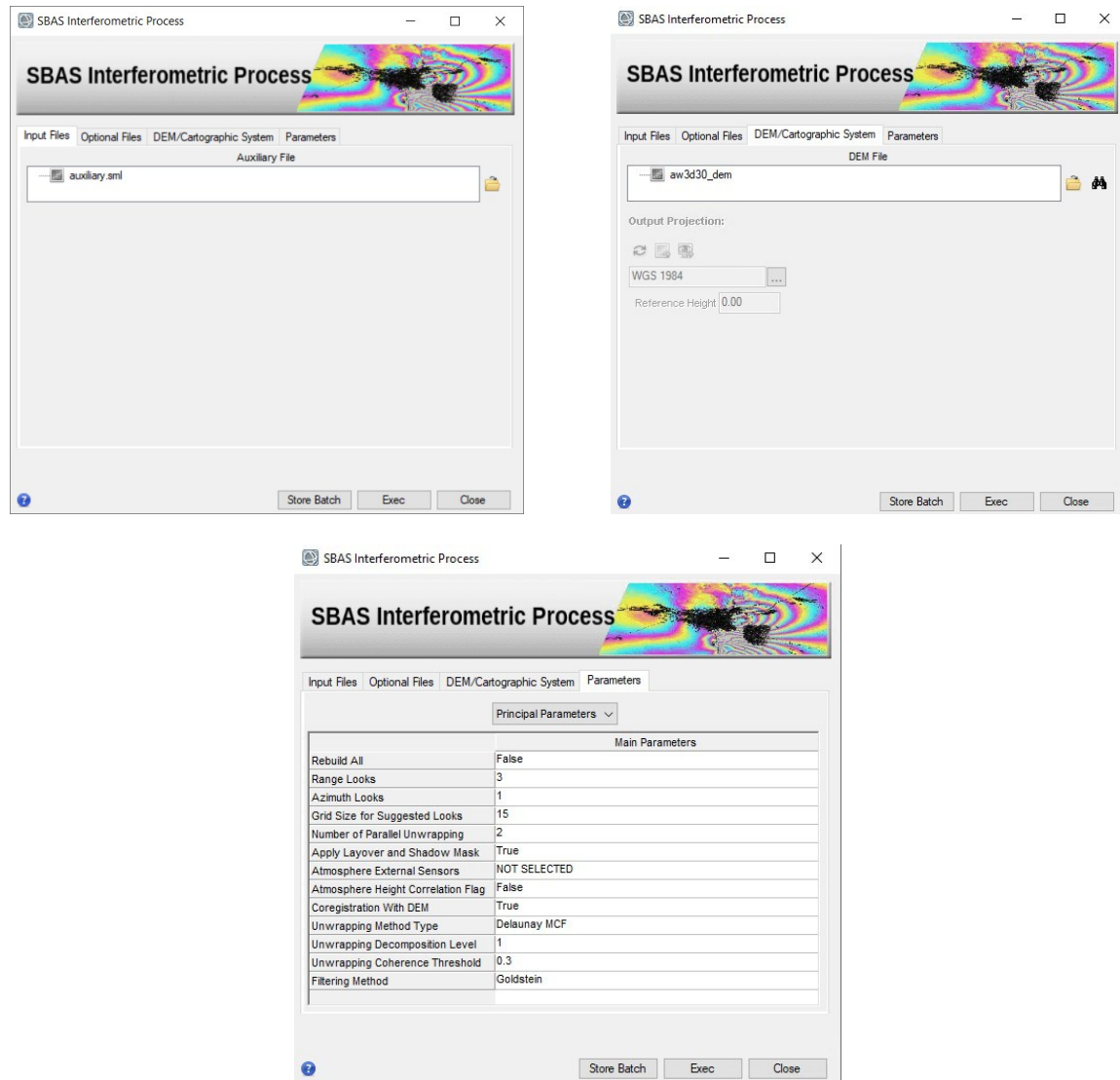


Figure 8 *Interferometric Process* panels.

Considering that the area under analysis is almost flat and the interferograms are well flattened by the reference DEM (coupled with the weak sensitivity to the topography of the Sentinel-1 orbital configuration), it is possible to use the *Delaunay MCF* technique for the unwrapping. This technique offers greater robustness around areas of low coherence while avoiding incorrect phase discontinuities compared to its *MCF* approach.

TIP Other important parameters that deserve to be mentioned in this step are the interferometric filter type and the interferometric filter intensity. The *Goldstein* filter offers an excellent quality-performance ratio, while the *Adaptive Non-Local InSAR* filter preserves more details as well as offers a better estimation of spatial coherence, at the expense of a larger computational time; therefore the *Adaptive Non-Local InSAR* filter is recommended for small datasets (in terms of number of interferograms and their pixel size, e.g., 1000x1000 pixels) as well as being bound to the use of a graphic processing units (GPU) to exploit its multithread optimization.

Output

Output layers are saved inside the *interferogram_stacking* folder. This directory contains the following products:

- Due to the large number of output products meta (*_meta*) and series (*.series*) files are generated. They enable to load at once all relevant output products.
- The *interf_tiff* sub-folder contains the tiff files of intermediate interferometric SBAS results.

Generated meta and series files:

- *IS_cc_meta, IS_cc.series*, which refers to all coherence images.
- *IS_fint_meta, IS_fint.series*, which refers to all flattened and filtered interferograms.
- *IS_clean_fint_meta, IS_clean_fint.series*, which refers to all flattened, filtered and cleaned (outputted by optional processes) interferograms.
- *IS_upha_meta, IS_upha.series*, which refers to all unwrapped phases.
- *IS_pwr_meta, IS_pwr.series*, which refers to all slant range intensity images.

The *work_interferogram_stacking* folder stores intermediate processing results.

To distinguish the incoming SAR pair from which each outgoing product comes (as well as to identify it in the connection network), a prefix containing the master-slave acquisition dates (e.g., Yyyymmdd) and the master-slave relationships will be added.

Please note that hereinafter *IS_* is the prefix used for *Interferometric Process* products.

After the *Interferometric Process* step, it is very important to check the intermediate products, in particular:

- the flattened and filtered interferograms, **_fint.tiff* files (also called wrapped interferograms).
- the unwrapped phases **_upha*.
- the coherence series **_cc*.

TIP To check the coherence and unwrapped phase files, upload in ENVI the *IS_cc.series* and the *IS_upha.series* from the *interferogram_stacking* folder. The ENVI Series Manager opens and allows users to quickly analyze the files. The visualization of the coherence files in grey scale is recommended (see Figure 9), the visualization of the unwrapped files in *rainbow* color scale is suggested (see Figure 11). For this reason, right click on the **_upha.series* file from the ENVI Layer Manager, and select Change Color Table/Rainbow. To check the **_fint.tiff* files a simple image viewer could be enough (see Figure 10).

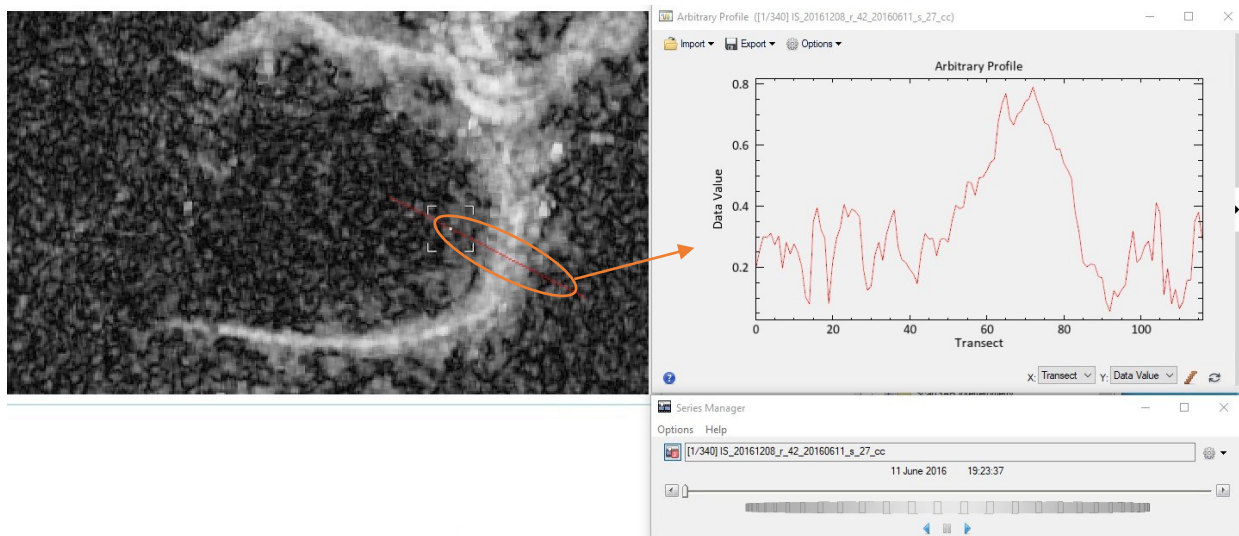


Figure 9 coherence transect for the *Unwrapping Coherence Threshold* evaluation.

TIP The coherence threshold value to be set in the *Interferometric Process* panel can be increased or decreased depending on the coherence values characterizing the study area (see Figure 9). This value must be increased if there are (on average) too many noisy areas that must be removed from the unwrapped stack not to compromise the result; anyway, it should not be increased too much, e.g., not more than 0.4-0.5, to preserve a sufficient spatial coverage.

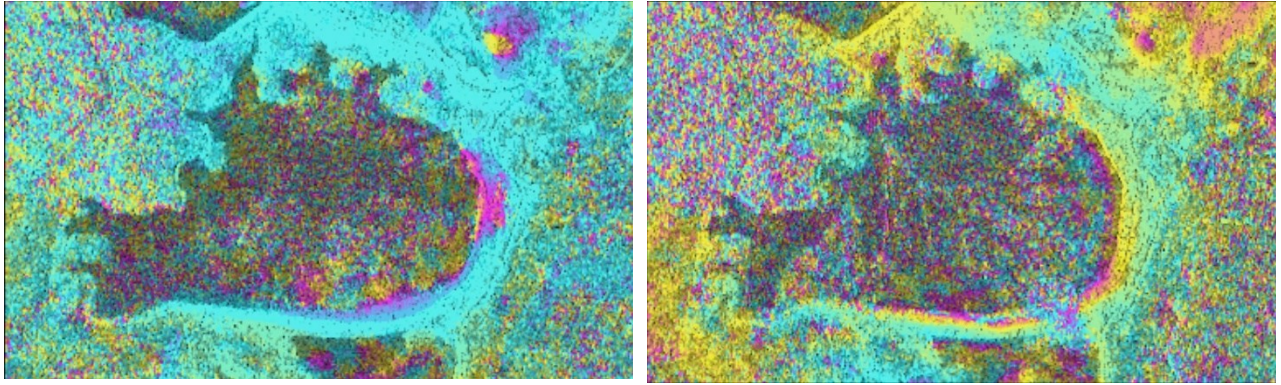


Figure 10 Filtered interferogram wrapped phase tiff. Pre-event interferogram on the left, co-event interferogram on the right.

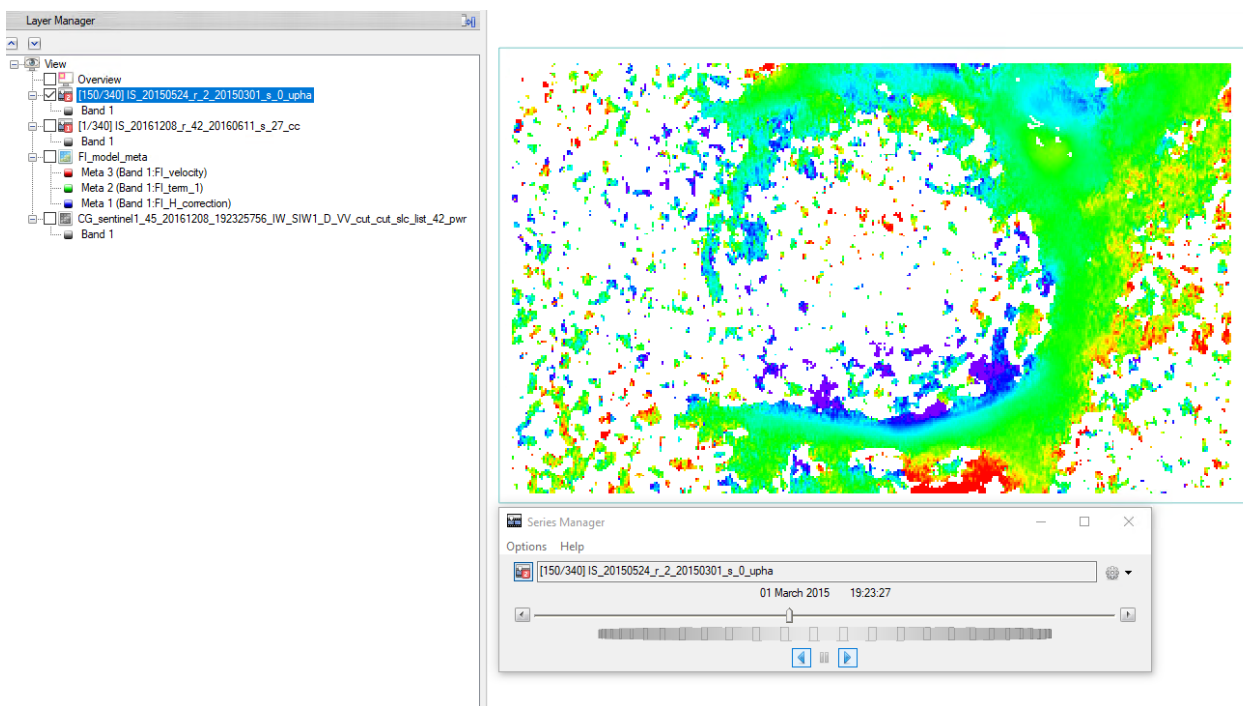


Figure 11 Unwrapped interferogram phase colored with the ENVI Rainbow color scale.

Observing the above-mentioned results anomalous behavior, such as inaccurate orbits phase ramp, uncoherent pairs, atmospheric artifacts, residual topography effects, can be detected.

TIP In case of some unwrapped interferograms are still characterized by very low coherence (visible as low coverage) or unwrapping errors, it is recommended to remove them from the interferometric stack with an Edit Connection Graph (see Annex 4), aiming to improve the result of the following SBAS inversions.

7. SBAS - Inversion: First Step

In this step, the parameters of the model fitting the trend of deformation according to the behavior of the area of interest are estimated. The parameter estimation is performed on the unwrapped interferogram stack (re-flattened *_reflat_upha), by inverting the corresponding system of equations. The matrix inversion is then carried on with a Single Value Decomposition (SVD) approach. Only the pixels characterized by a fully connected graph (subordinated to the imposed coherence threshold value), will be considered, and solved by the inversion. The result of this step will therefore typically be an **average displacement rate (v)** and a **topographic residual (h)** value. The No Displacement model is a custom method, where the SBAS is used as a high precision DEMs generator.

TIP It is advisable to start using a linear inversion model as fitting deformation model resulting the more robust and reliable choice. Other models (e.g., quadratic, cubic) require high connection graph redundancy and highly coherent interferograms to provide reliable results.

After the deformation trend estimation via SVD inversion, the known components are removed from the wrapped interferogram stack, to allow a second unwrapping (see Figure 12), with the aim of improving the unwrapped interferogram stack ingested by the *Inversion: Second Step*.

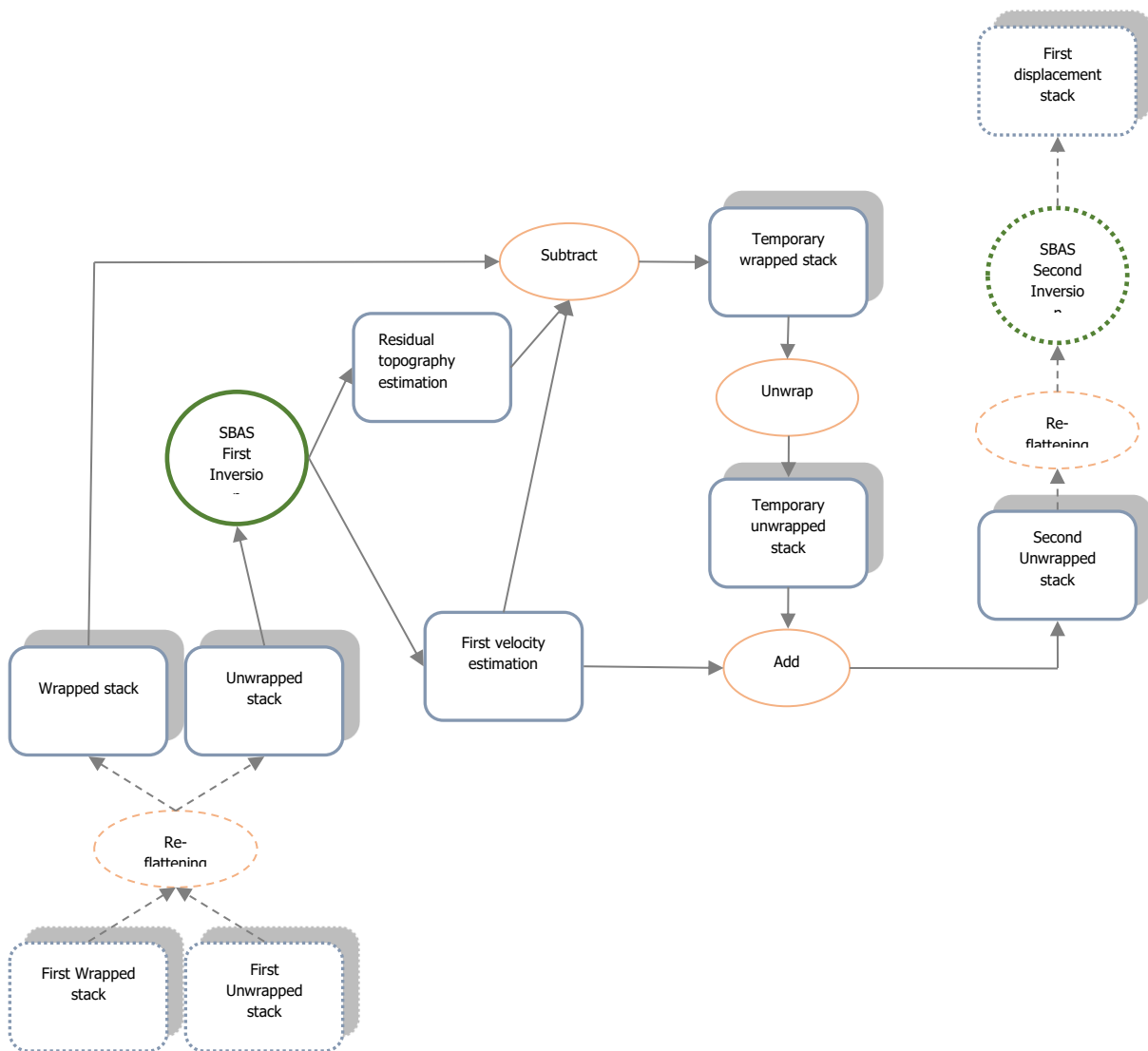


Figure 12 Second unwrapping detailed workflow.

The *Inversion: First Step* is performed running the */SARscape/Interferometric Stacking/SBAS & E-SBAS/3 - Inversion: First Step* panel (Figure 5 Figure 13).

Input files

Insert the *auxiliary.xml* file

Optional files

Refinement GCP file

Enter a previously created Ground Control Point file (Load GCP File .xml) or use the interface to create a new Ground Control Point file (Create GCP File, refer to the "Tools>Generate Ground Control Point" for details). This file is used for manual refinement. This file is optional and when it is not introduced, the software performs the refinement and re-flattening in an automated way.

See Annex 5 for more details.

Principal parameters

Rebuild All

By setting the flag the whole process is performed from scratch (if not incremental mode is active). It is advisable to leave this flag unchecked in case of process interruption, so that the products already generated have not to be computed and stored again.

Product Coherence Threshold

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

Displacement Model Type

The choice is given between the following models:

- *no displacement*, a stable area is considered, no displacement is calculated (this parameter set to true exploit the SBAS capability to calculate precise DEMs)
- *Linear*, the displacement velocity [mm/year] is calculated
- *Quadratic*, the displacement acceleration [mm/year²], and velocity [mm/year] are calculated
- *Cubic*, the displacement acceleration variation [mm/year³], the displacement acceleration [mm/year²] and velocity [mm/year] are calculated
- *Linear Periodic*, the periodic delay [days], the periodic modulation [mm] and velocity [mm/year] are calculated

The three displacement polynomial models can be synthesized as follows:

$$Disp = K_1 \cdot (t - t_0) + \frac{1}{2} \cdot K_2 \cdot (t - t_0)^2 + \frac{1}{6} \cdot K_3 \cdot (t - t_0)^3$$

where *Disp* is the displacement at time *t*; K1 is the linear term [mm/year], corresponding to the instantaneous displacement velocity; K2 is the quadratic term [mm/year²], corresponding to the instantaneous displacement acceleration; K3 is the cubic term, corresponding to the instantaneous displacement acceleration variation [mm/year³].

The displacement periodical model can be synthesized as follow:

$$Disp = K_1 \cdot (t - t_0) + K_2 \cdot \cos(2 \cdot \pi \cdot F \cdot (t - t_0) + K_3)$$

where *Disp* is the displacement at time *t*; K1 is the linear term, corresponding to the instantaneous displacement velocity; K2 is the modulation term [mm]; K3 delay [days]. F is the known expected frequency (1/ Model Period).

Estimate Residual Height

If selected, it estimates the residual topography height. This parameter should set to false in two situations:

- In case of good quality high reference resolution DEM, topography component estimation is not necessary.

- In case of less than 20 images, this could lead to a poor residual height estimation, and consequently a wrong velocity estimation, due to strong atmospheric artefacts. This could mostly happen for stacks with small normal baseline as Sentinel-1. The simplest model (with just one free term) increases the result reliability.

When this parameter is selected, and the *Displacement Model Type* selected is *no displacement*, the SBAS is used for the generation of precise DEMs.

Spatial Wavelet Size (m)

It preserves the estimated residual topography data resolution up to the specified value. It removes the low pass distortion under this resolution value and preserves the spatial details by using wavelet decomposition. If this value is smaller or equal to 0 is not considered.

Allow Disconnected Blocks

By setting this flag the program provides the solution for disconnected coherent targets over the grid point. The full graph connectivity is not a constraint anymore (refer to the Technical Note in the *Connection Graph*). The disconnected block SBAS provides a higher spatial coverage of the final results, limited by the *Min Valid Interferogram percentage* threshold.

The choices are the following:

- *False*: when the graph is not fully connected it is rejected.
- *Allow*: the results are provided even if the graph is not fully connected.

Min Valid Interferograms (%)

Percentage of the minimum number of accepted SBAS inversion equations (interferograms over the coherence threshold) for getting a result for each output grid point. This parameter is considered if it is equal or greater than zero and should be used when the *Allow Disconnected Blocks* is flagged (or the *Allow disconnected Blocks* has been previously flagged in the *Connection Graph* generation step). We suggest a threshold higher than 50% to have enough valid measurements to correctly calculate the SVD inversion.

Stop Before Unwrapping

By setting this flag, the phase unwrapping (last step of the processing sequence) is not executed.

Number of Parallel Unwrapping

Defines the number of unwraps that will be performed in parallel (one interferogram for each thread). This parameter must not exceed the total number of CPU threads. The user should consider the available system memory before increasing the number of parallel processes, as the memory consumption is directly related to the number of unwraps performed in parallel.

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.

Set the Unwrapping Method Type to *Delaunay MCF*

Unwrapping Decomposition Level

The number of under sampling levels to be applied to the complex interferogram before performing the phase unwrapping can be specified.

Unwrapping Coherence Threshold

Pixels with coherence values smaller than this threshold are not unwrapped and set at NaN.

Refinement Radius (m)

Maximum buffer radius for the association of Ground Control Point with respect of the slant range unwrapped phase closer valid pixel.

Refinement Residual Phase Poly 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 than 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.

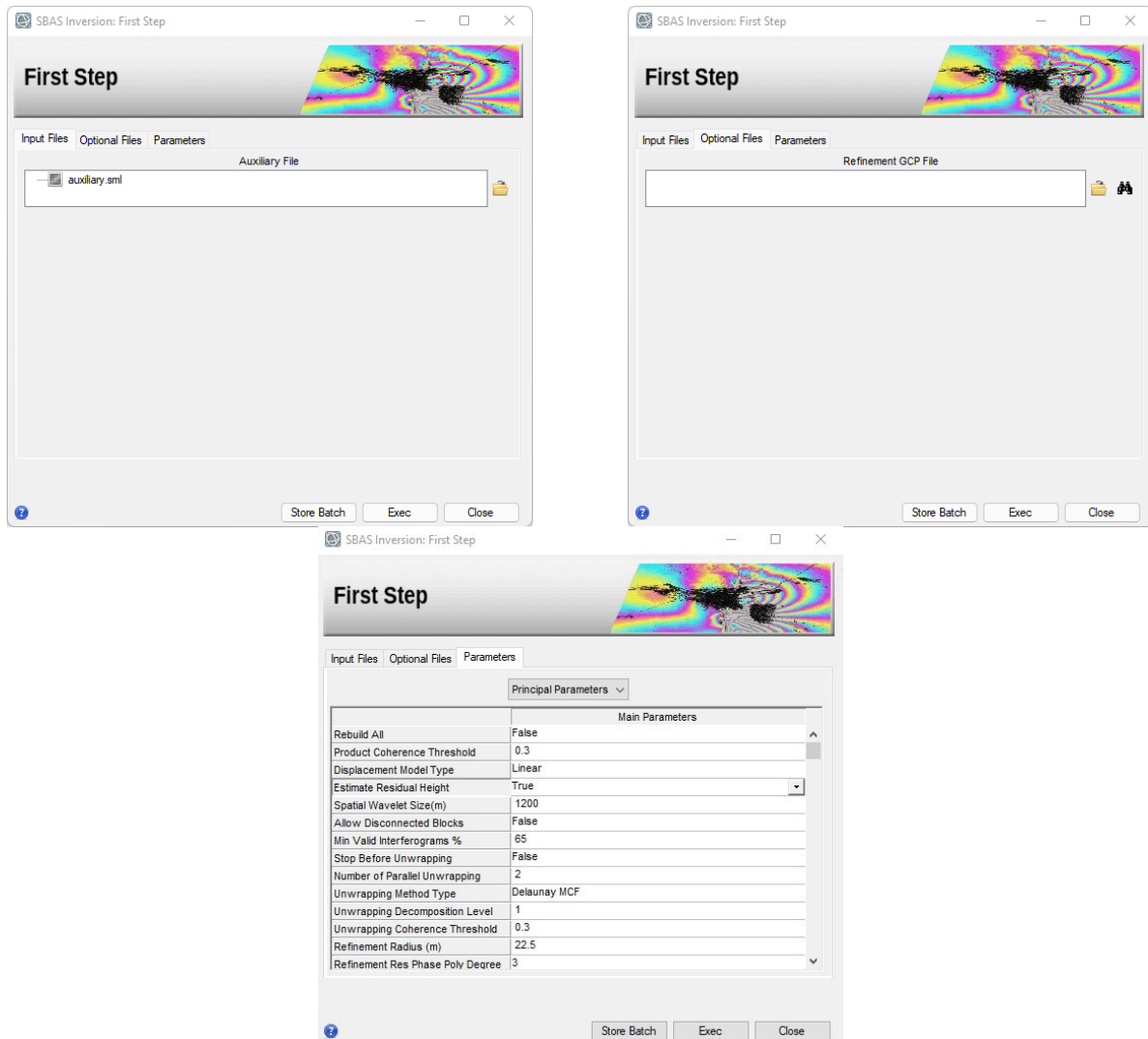


Figure 13 *Inversion: First Step* panel.

For this process, it was decided to use the automatic refinement and re-flattening: no GPCs are needed.

Considering that the area under analysis is almost flat and the interferograms are well flattened by the reference DEM, it is possible to use the "Delaunay MCF" technique for the unwrapping. This technique offers greater robustness around areas of low coherence while avoiding incorrect phase jumps compared to its "MCF" counterpart. Increase the coherence thresholds to 0.3, more suited for this high coherence area.

TIP During the second unwrapping performed in the First Inversion step it is possible to increase the *Unwrapping Decomposition Level* compared to the first unwrapping (e.g., Level 2 could be afforded) because the wrapped interferograms have been simplified (the estimated topographic residuals and the displacement model have been removed) and therefore the risk of aliasing is lower. Increasing the decomposition level could lead to improve the quality of the second unwrapping results as well as a greater speedup of the process.

Output

Note: The following warning message will appear:

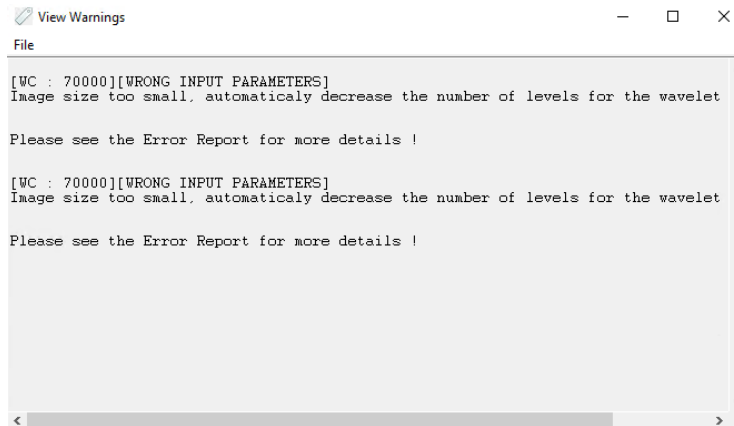


Figure 14 Wavelet size warning message.

Note that it is just a warning message that notifies the user that the wavelet level is too high compared to the size of the AOI, this level is then automatically adjusted by the software, so no actions are required from the user (the wavelet filter is designed to remove the low frequency component of the topographic residual, by keeping the low pass component of the reference DEM).

first_inversion folder

Directory containing the following products:

- Due to the large number of output products meta (*_meta*) and series (*.series*) files are generated. They enable to load at once all relevant output products.
- The "*interf_tiff*" sub-folder with the tiff files of intermediate interferometric SBAS results.
- The "*inversion*" sub-folder with the products (first model) from SBAS inversion in slant range geometry.

Generated meta and series files:

- *FI_reflat_upha_meta*, *FI_reflat_upha.series* which refers to the re-flattened upha.
- *FI_reflat_fint_meta*, *FI_reflat_fint.series* which refers to the re-flattened filtered complex interferograms.
- *FI_model_first_meta*, *FI_model_first.series* which refers to the residual height and displacement velocity (plus ancillary layers), obtained from the SVD inversion, in slant range geometry.
- *FI_second_fint_meta*, *FI_second_fint.series*, which refers to all re-flattened filtered interferograms. From these interferograms the estimated displacement model and the estimated residual topography has been removed. Note that this same extension is used for the 1st level unwrapped products, which are generated during the *Interferometric Process* step.
- *FI_second_upha_meta*, *FI_second_upha.series*, which refers to all unwrapped phases. From these unwrapped phases, the estimated model has been removed. Note that this same extension is used for the 1st level unwrapped products, which are generated during the *Interferometric Process* step.

The output results in the inversion folder consist of:

- height related products which are:
 - *FI_H_correction*, corresponding to the correction (in meters) with respect to the input Digital Elevation Model.
 - *FI_H_precision*, corresponding to the estimate in meters of the height average precision.
 - *FI_srdem*, corresponding to the corrected Digital Elevation Model in slant range geometry.
- displacement related products which are:
 - *FI_term_1*, corresponding to the first-degree term of the inversion polynomial [mm/year].
 - *FI_term_2*, corresponding to the second-degree term of the inversion polynomial [mm/year²].

- *FI_term_3*, corresponding to the third-degree term of the inversion polynomial [mm/year³].
- *FI_velocity*, corresponding to the average displacement velocity [mm/year].
- *FI_acceleration*, corresponding to the average displacement acceleration [mm/year²].
- *FI_delta_acceleration*, corresponding to the variation of the average displacement acceleration [mm/year³].
- *FI_periodical_modulation*, corresponding to the periodic model modulation [mm].
- *FI_periodical_delay*, corresponding to the periodic model delay [days].
- *FI_V_precision*, corresponding to the estimate in millimeter/year of the velocity average precision.
- **general products** which are:
 - *FI_coherence*, corresponding to the multi-temporal coherence. It shows how well the displacement trend fits with the selected model.
 - *FI_RMSE_rad*, is a measure of the inversion quality. It is the RMSE expressed in radians. The higher this value the worse the fitting and inversion quality.
 - *FI_interf_perc*, valid interferogram percentage.

The displacement values are reported with:

- Positive sign if the movement corresponds to a decrease of the sensor-to-target slant range distance.
- Negative sign if the movement corresponds to an increase of the sensor-to-target slant range distance.

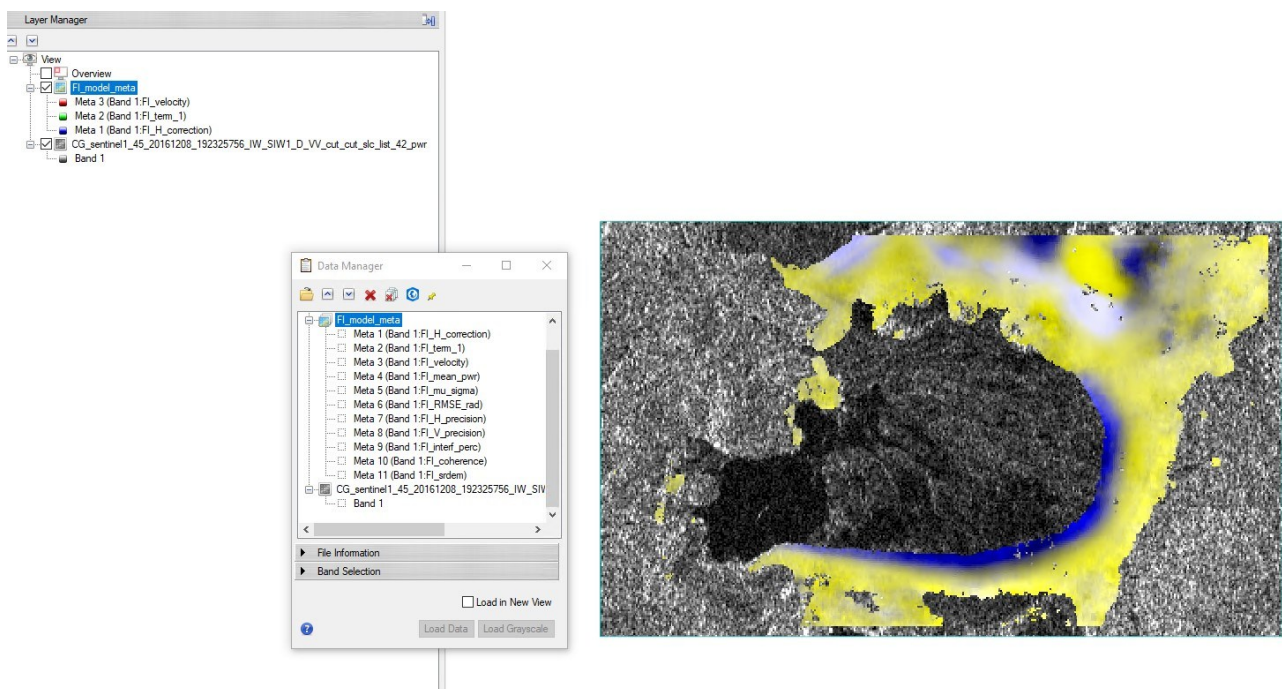


Figure 15 *FI_model_first_meta* products.

The average velocity, shown in Figure 16, is calculated in the following way: the displacement calculated over the considered period over the temporal interval. If the model chosen by the user is of the first order, the average velocity corresponds to the linear term K1. The mean acceleration and the change in mean acceleration are calculated in the same way in case of quadratic or cubic models.

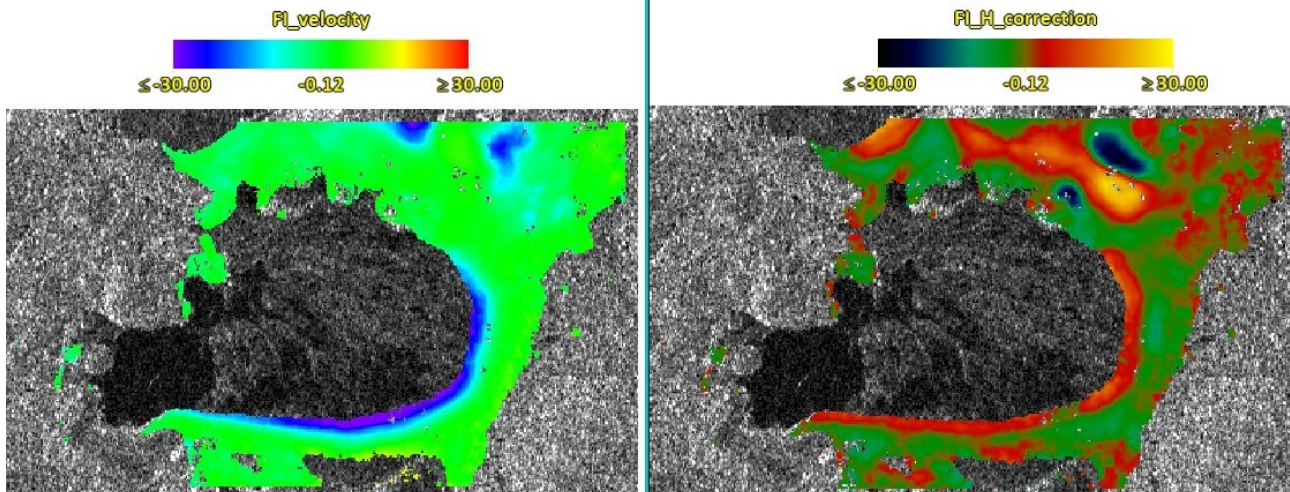


Figure 16 Average velocity first estimate (v) [mm/year] left, residual height estimation (h) [m] right.

8. SBAS - Inversion: Second Step

The *Inversion: Second Step* aims to estimate the final displacement time series [m], from the stack of unwrapped interferograms. The unwrapped interferograms are obtained from the previous SBAS step and should no longer contain any residual topography component. The unwrapped interferograms are firstly refined and re-flattened before being used as input to the SVD matrix inversion tool. The SVD inversion is used to solve the system of equations that describe the stack of unwrapped interferograms obtaining the displacements solution corresponding to each acquisition date. The displacement time series values are referred to the oldest date which is the reference zero.

Date-by-date displacements are filtered to remove atmospheric phase components: the filter preserves the displacement model component found during the *Inversion First Step*. Once the SVD matrix inversion has provided the "first estimate" of the displacement time series, the software temporarily removes the displacement model component, to preserve it during the Atmospheric Phase Screen (APS). The spatial LP and temporal HP filters are applied to the displacement time series. The resulting LP-HP layers (one for each acquisition) correspond to the contribution of atmospheric artifacts. These components can be checked using the corresponding series file in the work folder. The software removes atmospheric artifacts from the "first estimate" of the displacement time series, to obtain the final displacement time series. To increase the power of the HP-LP filter: decrease the size of the *LP window (meters)* and increase the size of the *HP window (days)*.

The final step is to derive the new displacement model as a regression of the filtered time series.

The *Inversion: Second Step* is performed running the `/SARscape/Interferometric Stacking/SBAS/5- Inversion` (Figure 5 Figure 17).

Input files

Insert the *auxiliary.sml* and the refinement GCPs file.

As for the generation of GCPs for refinement and re-flattening, refer to the considerations previously made, or simply use the same set of points previously generated.

TIP For this step it is possible to create a new set of GCPs to re-flat the unwrapped interferogram stack generated in the previous *Inversion: First Step*.

Optional files

Refinement GCP file

Enter a previously created Ground Control Point file (Load GCP File .xml) or use the interface to create a new Ground Control Point file (Create GCP File, refer to the "Tools>Generate Ground Control Point" for details). This file is used for manual refinement. This file is optional and when it is not introduced, the software performs the refinement and re-flattening in an automated way.

See Annex 5 for more details.

Principal Parameters

Rebuild All

By setting the flag the whole process is performed from scratch (if not incremental mode is active). It is advisable to leave this flag unchecked in case of process interruption, so that the products already generated have not to be computed and stored again.

Product Coherence Threshold

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

Interpol Disconnected Block

By setting this flag to true the program provides the solution for disconnected coherent targets over the grid point. The temporal gaps, where the displacement measurement does not exist or have been rejected, are interpolated using the average trend estimated during the first inversion. The disconnected SBAS provides a higher spatial coverage of the solution, limited by the *Min Valid Interferogram* and *Min Valid Acquisition percentage* thresholds.

The choices are the following:

- *False*: the temporal series with gaps are rejected.
- *Interpol using model*: the gaps are interpolated using the average trend estimated during the *Inversion: First Step*.
- *Interpol starting from zero*: the gaps are filled with zero. The temporal series start from zero at the end of each gap.

Min Valid Interferograms (%)

Percentage of the minimum number of accepted SBAS inversion equations (interferograms over the coherence threshold) for getting a result for each output grid point. This parameter is considered if it is equal or greater than zero and should be used when the *Interpol Disconnected Blocks* is flagged (or the *Allow disconnected Blocks* has been previously flagged in the *Connection Graph* generation step or *First Inversion Step*). We suggest a threshold higher than 50% to have enough valid measurements to correctly calculate the SVD inversion.

Min Valid Acquisitions (%)

Percentage for the minimum number of valid acquisitions (covered by at least a certain amount of valid interferogram over the coherence threshold) for getting an acceptable result, at each output grid point. This parameter is considered if is equal or greater than zero and should be used when the *Interpol Disconnected Blocks* is flagged (or the *Allow Disconnected Blocks* has been previously flagged in the *Connection Graph* generation step or *First Inversion Step*). We suggest a threshold higher than 80% to have enough valid measurements to correctly calculate the SVD inversion.

Atmosphere Low Pass Size (m)

Enter the window size, in meters, to apply the spatial distribution related filter.

Atmosphere High Pass Size (days)

Enter the window size, in days, to apply the temporal distribution related filter.

Refinement Radius

Maximum buffer radius for the association of Ground Control Point with respect of the slant range unwrapped phase closer valid pixel.

Refinement Residual Phase Polynomial Degree

Number of polynomial coefficients 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 than the number of input Ground Control Points, it will be automatically decreased. The default value 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.

Set the *Refinement Residual Phase Polynomial Degree* to 1

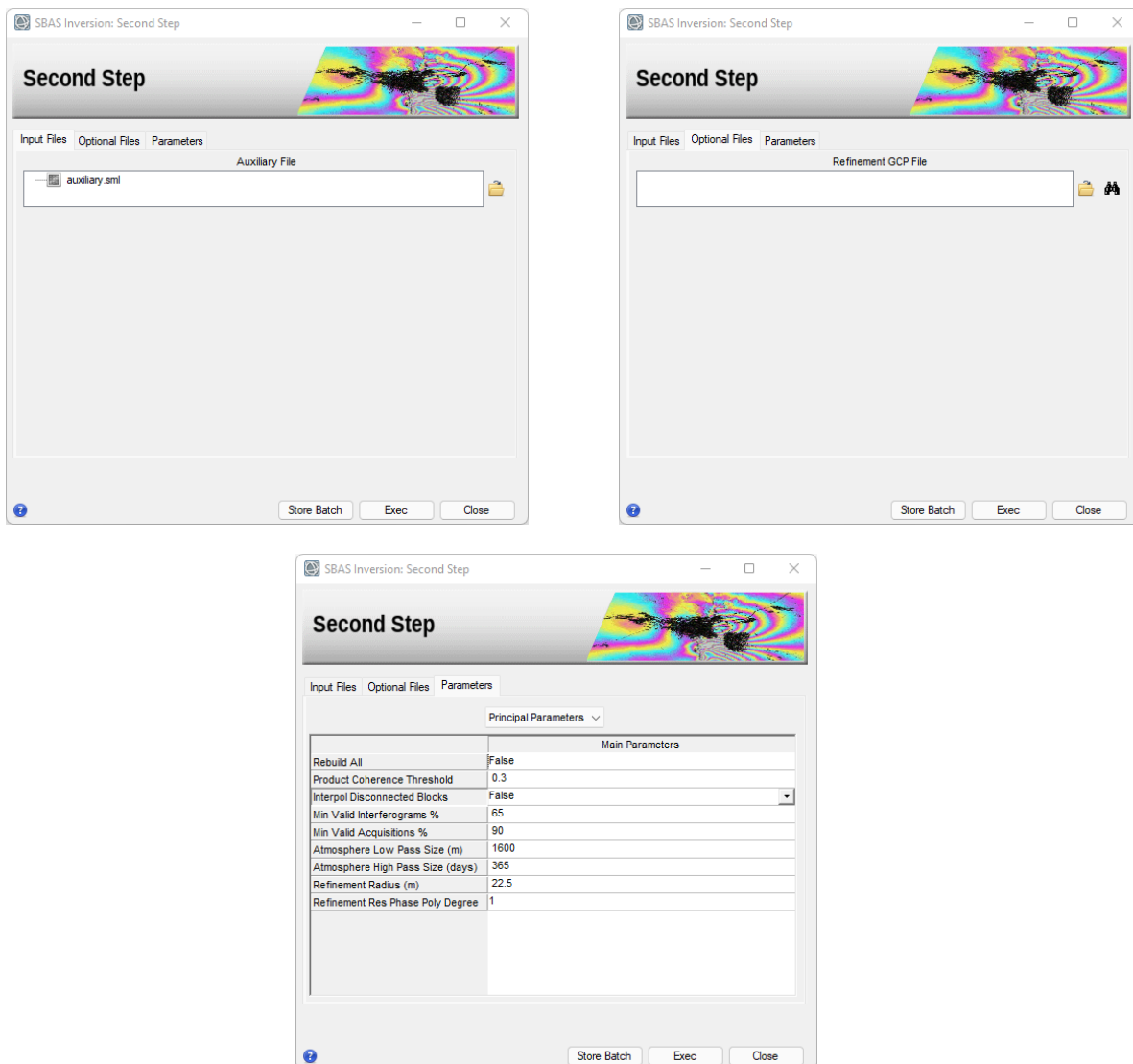


Figure 17 *Inversion: Second Step* panel.

For this process, it was decided to use the automatic refinement and re-flattening: no GPCs are needed.

Output

second_inversion folder

Directory containing the following products:

- Due to the large number of output products meta (*_meta*) and series (*.series*) files are generated. They enable to load at once all relevant output products:
- The "inversion" sub-folder with the products (second model) from SBAS inversion in slant range geometry.
- The internal copy of the input refinement and re-flattening GCP (*.xml*).
- The input refinement and re-flattening GCP converted in shape format in slant geometry (*.shp*).
- The input refinement and re-flattening GCP converted in shape format in geocoded geometry (*.shp* and *.kml*).

Generated meta and series files:

- *SI_model_meta, SI_model.series*, which refers to the residual height and displacement velocity (plus ancillary layers), obtained from the time series polynomial regression, in slant range geometry.
- *SI_disp_first_meta, SI_disp_first.series*, which refers to the date by date displacements, measured in slant range geometry, without atmospheric correction.
- *SI_disp_meta, SI_disp.series*, which refers to the date by date displacements, measured in slant range geometry, after the atmospheric correction.
- *SI_interf_counter_meta, SI_interf_counter.series*, which refers to valid measure (interferograms with coherence higher than the Product Coherence Threshold) counter for each acquisition.
- *SI_only_disp_upha_meta, SI_only_disp_upha.series*, which refers to all unwrapped phases flattened by the residual height estimated component
- *SI_second_reflat_upha_meta, SI_second_reflat_upha.series*, which refers to all unwrapped phases re-flattened for the second SVD inversion.

The output results in the inversion consist of:

- displacement related products which are:
 - *SI_term_0*, corresponding to the zero-degree term of the inversion polynomial [mm].
 - *SI_term_1*, corresponding to the first-degree term of the inversion polynomial [mm/year]. *SI_term_2*, corresponding to the second-degree term of the inversion polynomial [mm/year²].
 - *SI_term_3*, corresponding to the third-degree term of the inversion polynomial [mm/year³].
 - *SI_velocity*, corresponding to the average displacement velocity [mm/year].
 - *SI_acceleration*, corresponding to the average displacement acceleration [mm/year²].
 - *SI_delta_acceleration*, corresponding to the variation of the average displacement acceleration [mm/year³].
 - *SI_periodical_modulation*, corresponding to the periodic model modulation [mm].
 - *SI_periodical_delay*, corresponding to the periodic model delay [days].
 - *SI_disp_first_est*, corresponding to the date specific displacement (in millimeters) measured with respect to the first acquisition date, to which a null displacement is assigned, without atmospheric correction.
 - *SI_disp*, corresponding to the date specific displacement (in millimeters) measured with respect to the first acquisition date, to which a null displacement is assigned, after the atmospheric correction.
- general products which are:
 - *SI_coherence*, corresponding to the multitemporal coherence. It shows how much the displacement trend fits with the selected model.
 - *SI_RMSE_rad*, which is a measure of the inversion quality. It is the RMSE expressed in radians. The higher this value the worse the fitting and inversion quality.
 - *SI_RMSE_mm*, which is a measure of the fitting quality. It is the RMSE expressed in millimeters. The higher this value the worse the fitting and inversion quality.
 - *SI_norm_L1*, corresponding to the cumulated summation of the date-by-date absolute value displacements (in millimeters).
 - *SI_interf_counter*, counter with the valid measure number for each acquisition.
 - *SI_image_perc*, valid acquisitions percentage (covered by at least one valid measure).
 - *SI_interf_perc*, valid interferogram percentage.

The displacement values are reported with:

- Positive sign if the movement corresponds to a decrease of the sensor-to-target slant range distance.

- Negative sign if the movement corresponds to an increase of the sensor-to-target slant range distance.

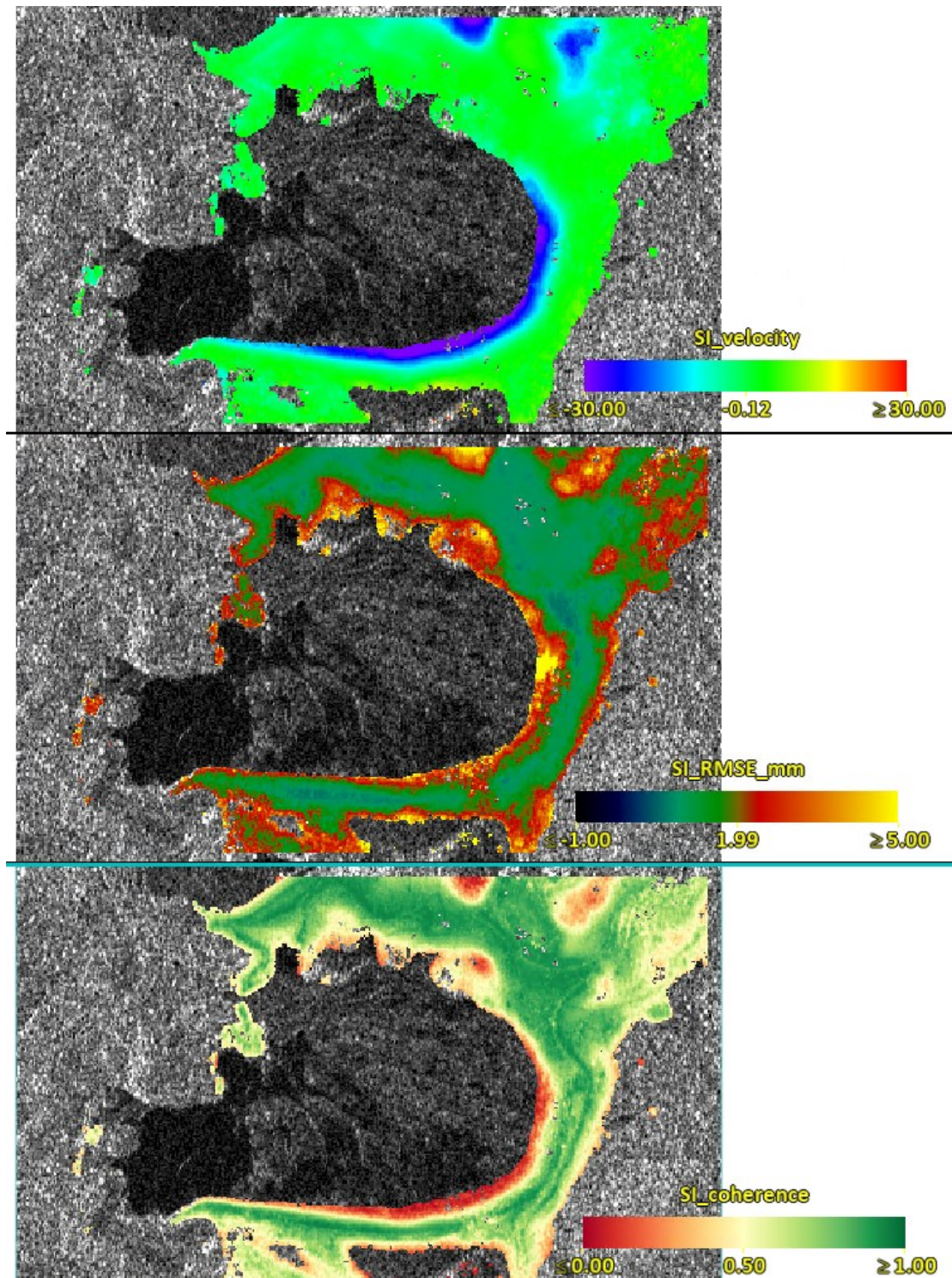


Figure 18 Average velocity final estimate (v) [mm/year] upper left, root means square error [mm] and temporal coherence. With the average amplitude image in background.

After the conclusion of the *Inversion Second Step* it is possible to analyze the meta file containing the principal products: *SI_model_meta* (see Figure 18), in addition to the time series before (*SI_disp_first_meta*) and after

(*SI_disp_meta*) the removal of the atmospheric contribution, using the dedicated tool *Time series Analyzer Raster*.

TIP The analysis and the comparison between the “first estimation” time series and the final time series, could be useful to calibrate the intensity of the atmosphere filtering. This analysis is also useful to highlight any anomalies on the spatial and temporal deformations that are not properly treated from the atmospheric filter. This could happen in case of strong wide and sudden events such as an earthquake (a phenomenon which behavior is similar to that of the atmosphere, and therefore could be removed or degraded by the APS filter).

Note: To proceed with the E-SBAS processing, it is sufficient to complete the SBAS processing chain up to the Second Inversion step and loading the SBAS auxiliary file in the *E-SBAS Connection graph* tool. However, if the user wants to generate the final SBAS output, it is necessary to perform the last step: Geocoding.

For this process, it was decided to use the automatic refinement and re-flattening: no GPCs are needed.

9. SBAS - Geocoding

SBAS products are firstly refined and re-flattened before proceeding to the geocoding. Geocoded products can be displayed in two types of formats: Shape and/or Raster based on the flag selected in the parameters.

The *Geocoding* step is performed running the */SARscape/Interferometric Stacking/SBAS & E-SBAS/5 - Geocoding* (Figure 5 Figure 19).

Input files

Insert the auxiliary.sml file.

Optional files

Refinement GCP file

Enter a previously created Ground Control Point file (Load GCP File .xml) or use the interface to create a new Ground Control Point file (Create GCP File, refer to the "Tools>Generate Ground Control Point" for details). This file is used for manual refinement. This file is optional and when it is not introduced, the software performs the refinement in an automated way.

See Annex 5 for more details.

Shape Mask File

The user can create a shapefile (.shp) that contains the area to discard, this shapefile must be geocoded (with the same carto-system of the reference DEM). The subsequent step will take this shape into account to remove the pixel inside the mask area from the geocoding step. This file is optional.

DEM / Cartographic System

Insert the *aw3d30_dem* provided in the dataset.

Principal Parameters

Rebuild All

This flag refers to all SBAS process. By setting the flag the whole process is performed from scratch (if not incremental mode is active). It is advisable to leave this flag unchecked in case of process interruption, so that the products already generated have not to be computed and stored again.

Height Precision Threshold

Upper threshold of the height measurement average precision values (refer to the *Phase to Height Conversion* tool for more details). This must be provided in meters. This threshold is used together with the *Velocity Precision Threshold* and the *Product Temporal Coherence Threshold* for the masking process.

Velocity Precision Threshold

Upper threshold of the velocity measurement average precision values (refer to the *Phase to Displacement Conversion* tool for more details). This must be provided in millimeter/year. This threshold is used together with the *Height Precision Threshold* and the *Product Temporal Coherence Threshold* for the masking process.

Product Temporal Coherence Threshold

Lower threshold of the temporal coherence measurement values. This threshold is used together with the *Height Precision Threshold* and the *Velocity Precision Threshold* for the masking process.

Water Mask (dB)

Value in dB used as threshold to retrieve a water body mask from the average intensity image. All the points under this threshold will be removed from the output layers. Active if smaller than 0. We suggest to set a value of -10 or smaller.

Make Geocoded Raster

By setting this flag the output raster file/s are generated.

Make Geocoded Shape

By setting this flag the output shape file/s are generated.

Shape Max Number of Points

If values other than -1 are entered, the output shape file is split in several parts (each marked by a progressive numbering - _1; _2; etc.); each part of the shape contains a portion of the total number of points, which corresponds to the value entered. It is suggested not to exceed 200000 points to avoid visualization problems.

Generate Shape Time Series

By setting this flag the output shape file/s, with the displacement temporal evolution, are generated.

Generate Shape Counter Series

By setting this flag the output shape file/s, with the valid interferogram counter for each acquisition date, are generated. When the counter is zero, the correspondent acquisition date has been temporally interpolated. Higher the counter higher is the reliability of the corresponding estimated displacement measure.

Vertical Displacement

By setting this flag the displacements and velocity products are projected on the vertical direction. Do not use the reprojection if the real displacement direction is unknown.

Slope Displacement

By setting this flag the displacements and velocity products are projected on the vertical direction. Do not use the reprojection if the real displacement direction is unknown.

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. Do not use the reprojection if the real displacement direction is unknown.

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.

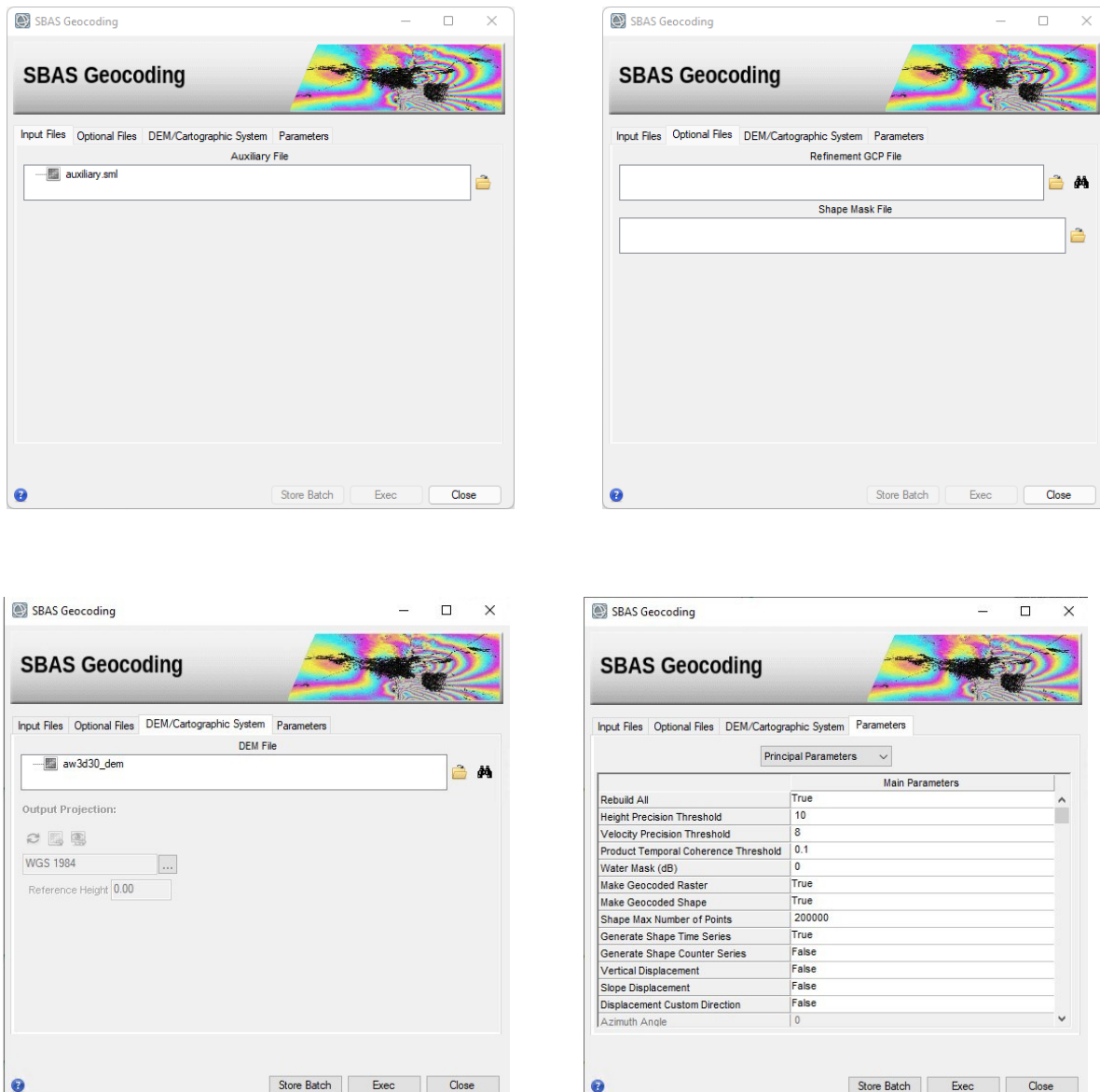


Figure 19 Geocoding panels.

For this process, it was decided to use the automatic refinement and re-flattening: no GPCs are needed.

To improve the masking of the geocoded products, it was decided to keep the *Height Precision*, the *Velocity Precision*, and the *Product Temporal Coherence* thresholds unchanged, and to act only on the *Water Mask* threshold. After evaluating the backscatter values on the water drawing a transect profile (see **Error! Reference source not found.**) on the *SI_mean_pwr* over the water, it was decided to use 0.06 as backscatter threshold to mask the water areas, which corresponds to -12dB ($10 \cdot \log 0.06$).

Output

Geocoding folder

Directory containing the following products:

- Due to the large number of output products meta (*_meta*) and series (*.series*) files are generated. They enable to load at once all relevant output products:
- The "*raster*" sub-folder with the products in raster version.
- The "*vector*" sub-folder with the products in shape version.

Generated meta and series files:

- *G_model_geo_meta*, which refers to the height and displacement velocity measurements (plus ancillary layers) in the output cartographic projection.
- *G_disp_first_geo_meta*, which refers to the date-by-date displacements, measured in the output cartographic projection, without atmospheric correction.
- *G_disp_geo_meta*, which refers to the date-by-date displacements, after the atmospheric correction, in the output cartographic projection.
- *G_interf_counter_geo_meta*, which refers to valid measure counter for each acquisition.

The output results in "*raster*" folder consist of:

- displacement related products which are:
 - *G_FI_velocity_geo*, corresponding to the first inversion mean displacement velocity [mm/year]. This raster is the result when *G_SI_velocity_geo* is not present.
 - *G_FI_acceleration_geo*, corresponding to the first inversion mean displacement acceleration [mm/ year²]. This raster is the result when *G_SI_acceleration_geo* is not present.
 - *G_FI_delta_acceleration_geo*, corresponding to the first inversion mean displacement acceleration variation [mm/ year³]. This raster is the result when *G_SI_delta_acceleration_geo* is not present.
 - *G_SI_velocity_geo*, corresponding to the second inversion mean displacement velocity [mm/year].
 - *G_SI_acceleration_geo*, corresponding to the second inversion mean displacement acceleration [mm/ year²].
 - *G_SI_delta_acceleration_geo*, corresponding to the second inversion mean displacement acceleration variation [mm/ year³].
 - *G_SI_term_0_geo*, corresponding to the zero-degree term of the second inversion polynomial [mm].
 - *G_SI_term_1_geo*, corresponding to the first-degree term of the second inversion polynomial [mm/year].
 - *G_SI_term_2_geo*, corresponding to the second-degree term of the second inversion polynomial [mm/year²].
 - *G_SI_term_3_geo*, corresponding to the third-degree term of the second inversion polynomial [mm/year³].
 - *G_FI_V_precision_geo*, corresponding to the velocity measurement average precision [mm/year] (refer to the *Phase to Displacement Conversion* for more details).
 - *G_SI_DDDDDDD_X_disp_geo*, corresponding to the date specific displacement [mm] measured with respect to the first acquisition date, to which a null displacement is assigned. Where DDDDDDD is the acquisition date and X the incremental date ID.
 - *G_SI_DDDDDDD_X_disp_first_geo*, corresponding to the date specific displacement [mm] measured with respect to the first acquisition date, to which a null displacement is assigned, without atmospheric removal. Where DDDDDDD is the acquisition date and X the incremental date ID.
- general products which are:
 - *G_FI_H_correction_geo*, corresponding to the first inversion correction [m] with respect to the input Digital Elevation Model. This raster is the result when *G_SI_H_correction_geo* is not present.
 - *G_SI_H_correction_geo*, corresponding to the second inversion correction [m] with respect to the input Digital Elevation Model.
 - *G_FI_H_precision_geo*, corresponding to the height measurement average precision [m] (refer to the *Phase to Displacement Conversion* for more details).
 - *G_FI_DEM*, corresponding to the first inversion corrected Digital Elevation Model [m]. This raster is the result when *G_SI_DEM* is not present.
 - *G_SI_DEM*, corresponding to the second inversion corrected Digital Elevation Model [m].

- $G_SI_RMSE_mm_geo$, which is a measure of the fitting quality geocoded. It is the RMSE [mm]. The higher this value the worse the fitting and inversion quality.
- $G_SI_DDDDDD_X_interf_counter_geo$, corresponding to the valid measures counter per each date.
- $G_SI_interf_perc_geo$, valid interferogram percentage.
- $G_SI_image_perc_geo$, valid acquisitions percentage (covered by at least one valid measure).
- $G_SI_disc_counter_geo$, disconnection counter (SBAS disconnected blocks disconnection counter).
- G_ALOS_geo , Azimuth Line of Sight. Positive angles are measured clockwise from the North; negative angles are measured counterclockwise from the North.
- G_ILOS_geo , Incidence angle of the Line of Sight. The angle is measured between the Line Of Sight and the vertical on the ellipsoid (flat earth).

The output results in "vector" folder consist of:

- $G_vVdV_hHdH_cCdC_X.shp$ where VdV is the precision velocity threshold, HdH the height precision threshold, CdC the temporal coherence threshold and X the shape part id. Shapefile of the SBAS with the associated files (.shx, .dbf and Google Earth .kml). If the number of points is larger than the *Shape Max Nr of Points*, several shapefiles are created.

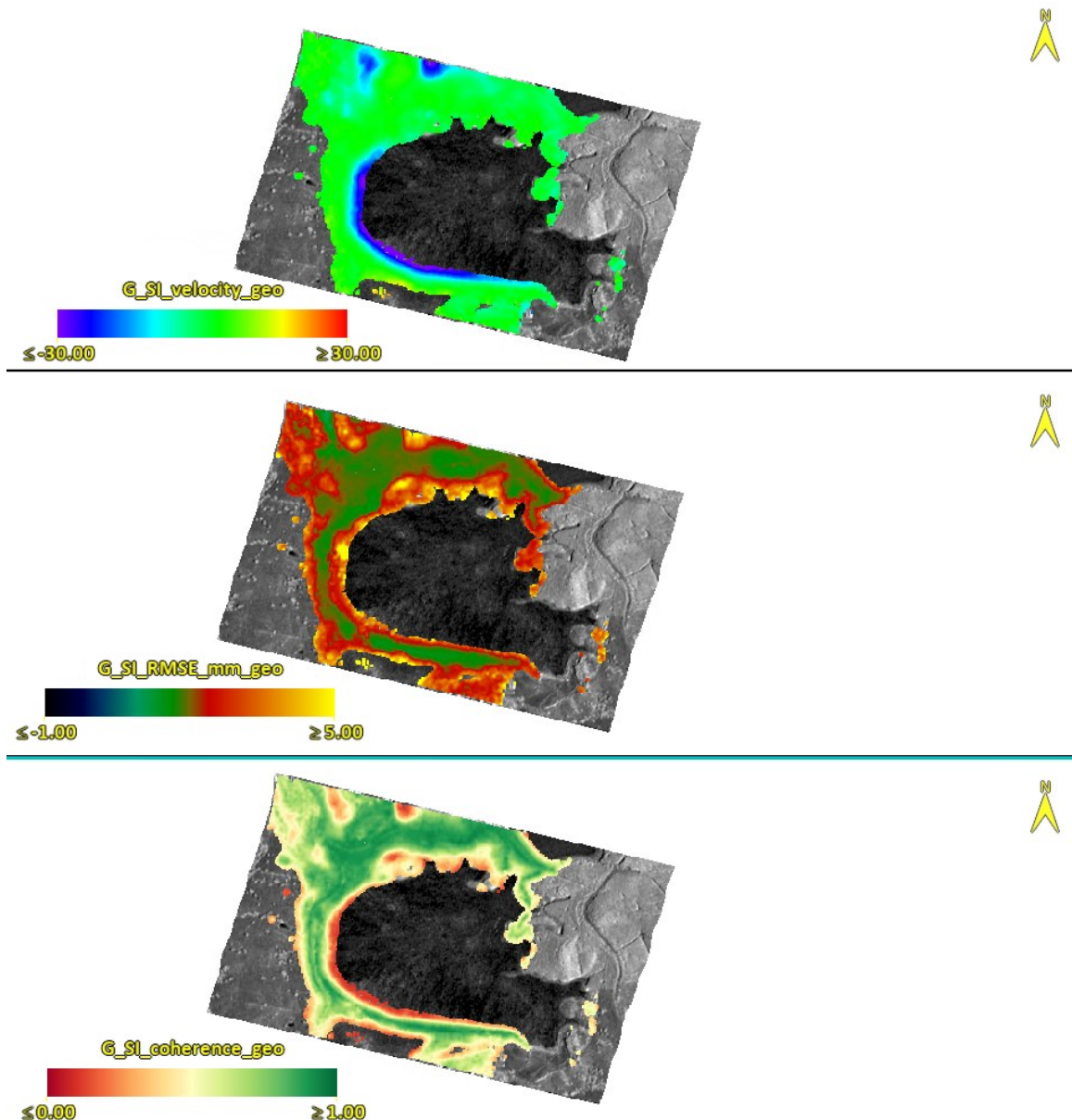


Figure 20 Geocoded final average displacement rate ($G_SI_velocity_geo$), Root Mean Square Error [mm] ($G_SI_RMSE_mm_geo$), Coherence ($G_SI_coherence_geo$) and average amplitude image ($G_FI_mean_pwr_geo$) in background.

The analysis of the time series can be performed both on the displacement stack in raster format (using the corresponding meta file) and on the generated shapes. The visualization tools are found in the *General Tools* menu: *Time Series Analyzer Raster* and *Time Series Analyzer Vector*, respectively. The shapes provide the product measures in point cloud format with a precise geolocation in 3D (i.e., at the maximum resolution obtainable from the available multi-looked slant range geometry dataset), while the meta raster provide a grid of product measures regularized in 2D (at the sampling specified by the user with *X Dimension (m)* and *Y Dimension (m)*), averaged and interpolated. See Annex 2 and Annex 3 to have more details about the plot of deformation time-series.

The analyses of the different output layers can help on understanding the deformation behavior of the study area and its temporal evolution.

In particular, the mean velocity of deformation is helping on identifying unstable areas, but is not providing information on the evolution of deformation, that is provided from each pixel time series. An additional information can be retrieved from the RMSE, describing how the deformation model (in this case a linear model) is able to fit the deformation behavior. Therefore, in case of high RMSE values, a certain divergence from the deformation model can be identified.

Figure 21 show two exemplificative stable points characterized but a low and a high RMSE (1 and 6 respectively).

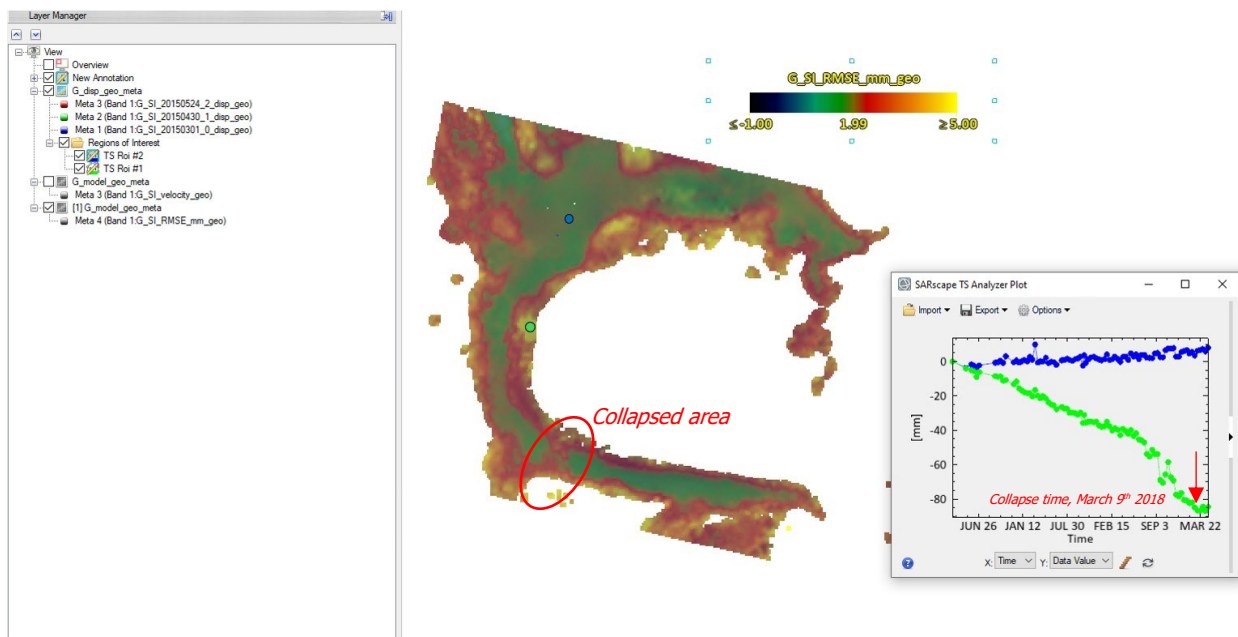
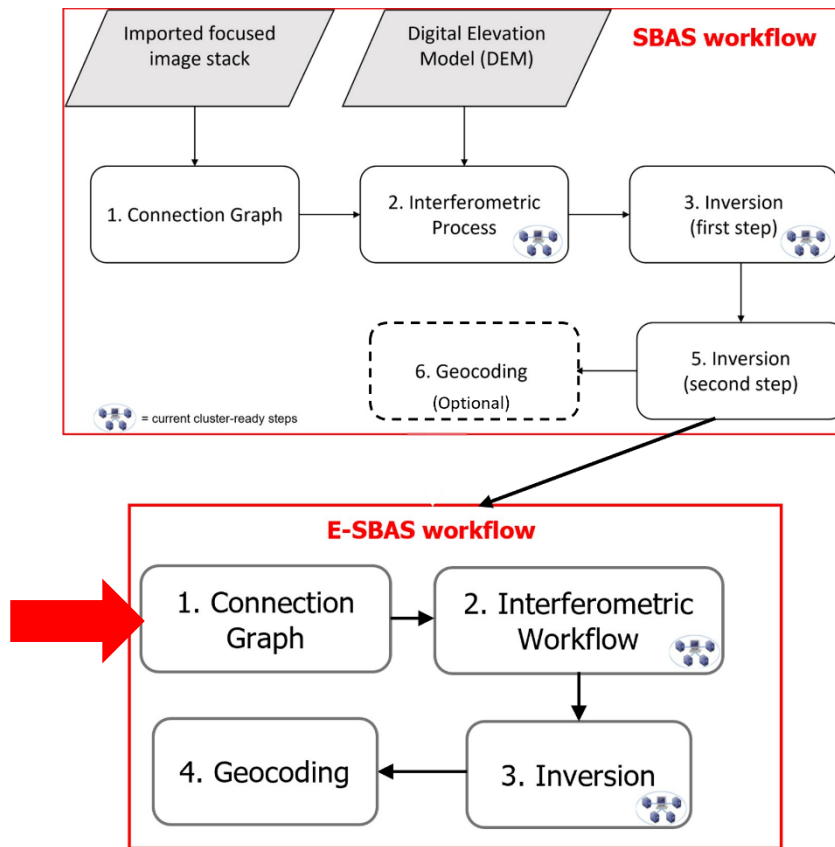


Figure 21 Time-series of two stable points characterized by a low RMSE (blue curve) and high RMSE (green curve). The collapsed area is highlighted on the map while the collapse time is highlighted in the displacement time series.

9. E-SBAS – Connection Graph



This functionality defines the SAR pair combination (Reference and Secondary images) and connection network, which is used for the generation of the multiple differential interferograms. This step is mandatory.

The pairs are shown as connections in a network that links each acquisition to the Master file. Given N acquisitions, the maximum theoretical available connections are $N-1$. For each pair, an interferogram is generated in the Interferometric Process.

Notes:

- This tool requires the auxiliary file from the SBAS processing, which needs to be computed up to the second inversion step.
- The E-SBAS processing does not apply any coherence threshold to discard pixels from the final output of each processing step. The processing mask is retrieved from the SBAS processing previously performed.

The *Connection Graph* is performed running the */SARscape/Interferometric Stacking/SBAS & E-SBAS/1 - Connection Graph* panel (see Figure 5).

Input files

Auxiliary SBAS File

Reference file generated as output of the "Second Inversion" step of the SBAS processing. This file is mandatory.

Optional file

Leave the Input Master file empty (this file is automatically chosen by SARscape).

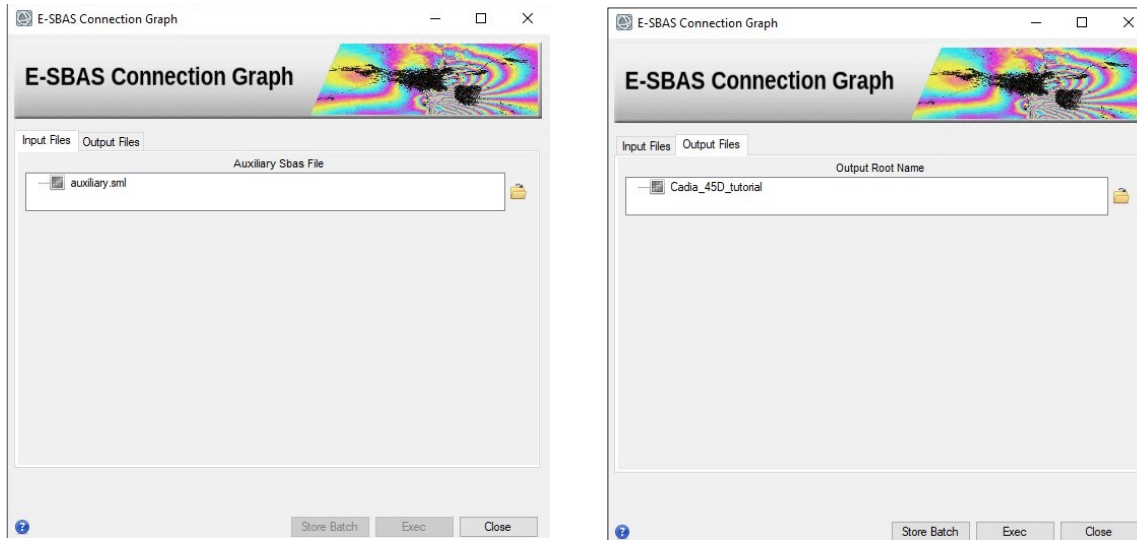


Figure 22 *Connection Graph* panels.

Output Files

Choose the location of the processing folder and an Output Root name.

The Output Root Name is used to create the processing folder. The folder name is given by the following composition: "Output Root Name"_ESBAS_processing.

Once the E-SBAS Connection Graph process is completed, a report and two graphs are displayed (Figure 6). The graphs are:

- *Time-Position plot*, which provides the relative normal distance between the acquisitions in meters (y axis), and the input acquisition dates (x axis). The *Time-Position plot* allows users to visually understand if the graph is fully connected and matches with required redundancy criteria. The higher the connection the most reliable displacement estimates.
- **TIP** The theoretical minimum average number of connections per acquisition is 5; we suggest an ideal configuration of 10 connections per acquisition. Obviously, as you increase the number of connections, the computational time is increasing.
- *Time-Baseline plot*, which provides the normal baseline in meters (y axis) and the input acquisition dates (x axis). This graph shows the interferogram coverage for each date.

Each acquisition is represented by a diamond. The color of the diamond symbol is as follows:

- Red: discarded acquisitions due to user specific constraints.
- Green: valid acquisitions.
- Yellow: Super-Master acquisition. The Super-Master is the reference image of the whole processing, and all the processed slant range pairs are co-registered and overlaid to this reference geometry.

TIP The graphs can be reloaded at any processing step from */SARscape/Interferometric Stacking/Stacking Tools/Plot Viewer* panel by adding the auxiliary file.

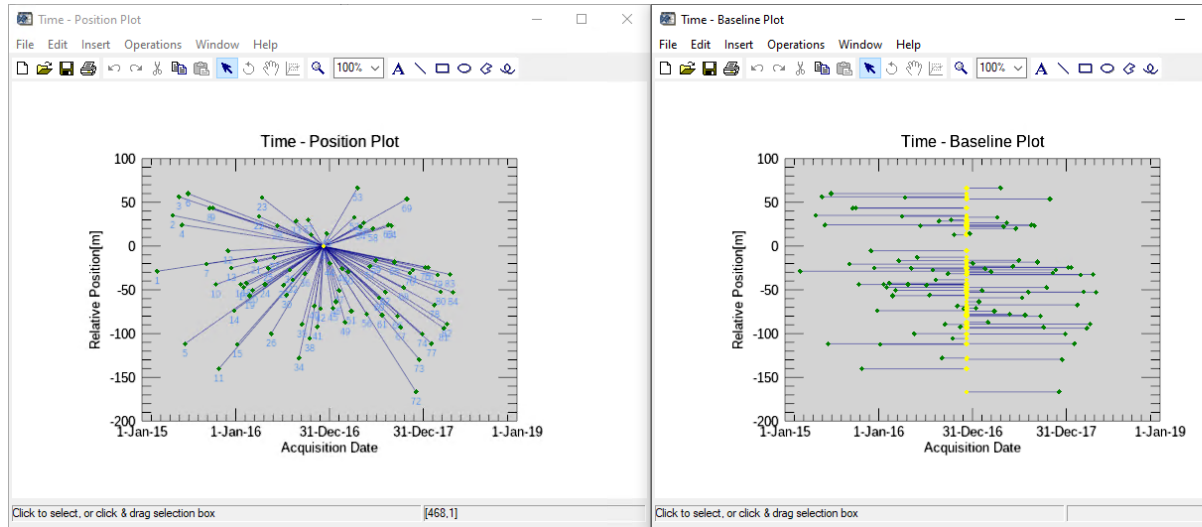


Figure 23 Plots generated by the *Connection Graph* tool.

In addition to the plots, the multi-looked Super-Master image (suffix, "_pwr") is also generated and displayed in ENVI (Figure 7). The multi-looked factor is automatically computed based on the grid size specified for the sensor once the *Preferences specific* are set.



Figure 24 Multi-looked Super Master image.

The *Connection Graph* step generates the *auxiliary.sml* file, the connection graph folder results, and the work folder.

The auxiliary file is the principal file that guide users in the SBAS processing, all the mandatory SBAS steps are based on the auxiliary file (see Annex 1).

The Connection graph folder includes:

- *CG_report.txt*, which summarizes the graph pairs characteristic, such as the total number of interferograms that shall be generated by the *Interferometric Process* step and involved in the following steps.
- *plot* sub-folder, which is used to store the files (*CG_baseline.txt* and *CG_position.txt*) necessary for the visualization of the graphs in ENVI.

The work folder includes sub-folders. The subfolders are created in the work folder once each step of the SBAS processing chain is run, and their name is automatically given by the step name.

It is worth to mention that the *parameters.sml* file is also created in the work folder. In this file all the set parameters used in that processing are recorded.

9. E-SBAS – Interferometric Process

The Interferometric Process step includes the following processing steps:

- Co-registration
- Differential interferogram generation

The interferometry step generates a set of N-1 interferograms in full resolution, no multilooking or filtering is applied.

The E-SBAS Interferometric Process is performed running the */SARscape/Interferometric Stacking/SBAS & E-SBAS/E-SBAS/2 - Interferometric Process* (Figure 8).

Input files

Insert the *auxiliary.sml* file.

Optional file

Leave the Geometry GCP file empty.

The GCP file is used to correct the master image in case of orbit inaccuracy (i.e. Master acquisition of the interferometric stack) based on the elevation value specified onto the Digital Elevation Model.

DEM/Cartographic System

Insert the *aw3d30m_dem* provided in the dataset.

Parameters

Leave the default parameters.

- *Generate Dint Multilooked for Quick View*
False is set by default. Set to True to generate differential interferograms, with the multilooking factors for a visual interpretation.
- *Rebuild all*
False is set by default. Set to True to start the whole process from scratch.
- *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).
- *Coregistration with DEM*
True is set by default. Set to False to avoid using the input Digital Elevation Model in the coregistration process.

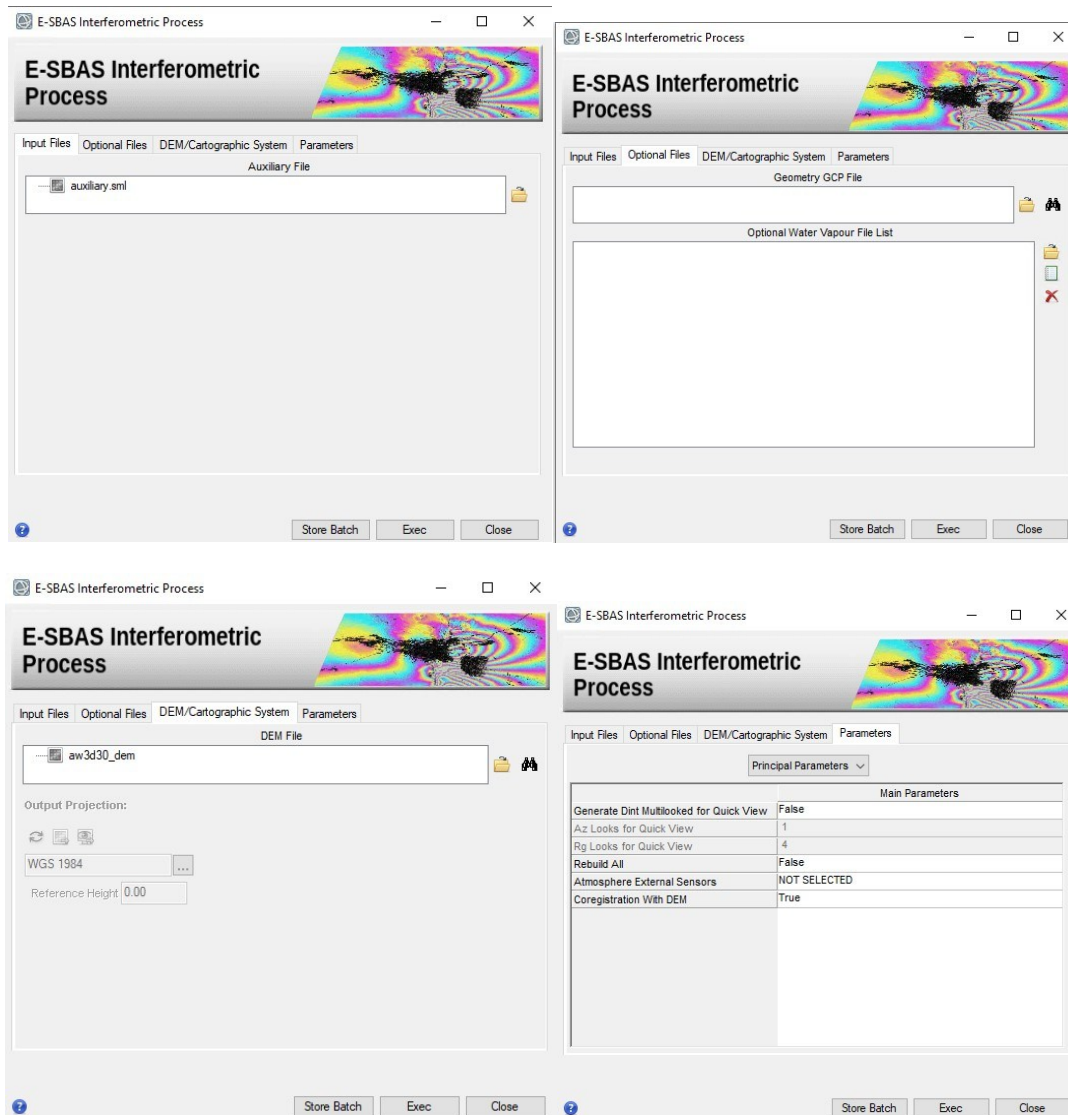


Figure 25 Interferometric Process panels.

Output

The **interferogram_stacking** folder includes:

- **Meta** files allowing to load the specific processing results (_meta)
 - slant_dint_meta, which refers to all flattened interferograms
 - slant_pwr_meta, which refers to all slant range intensity images
- **IS_srdem**: the synthetic DEM.

Note:The following files are going to be stored in this folder but they are going to be derived in the following step, the first inversion step:

- **mean**: SAR Intensity average raster file and associated header files (.sml, .hdr).
- **mu_sigma**: amplitude dispersion index (generated in inversion first step).

After the interferometric step, it is very important to check the first results, in particular if the coregistration step has worked well and therefore all slc data have been coregistered. The single _dint files are also stored inside the following folder: *ProjectName_ESBAS_processing|work|work_interferogram_stacking*.

10. E-SBAS – Inversion

This is the inversion step, which uses the SBAS products coming from the second SBAS inversion to initialize the E-SBAS inversion to estimate the atmospheric phase components.

The model inversion is implemented to derive the date by date displacements, after removing the low pass component coming from the SBAS, the atmospheric phase part of the signal and eventually fit the high pass displacement and velocity components.

The re-flattened interferograms are used to estimate the displacement related information (i.e. velocity, residual heights and date specific displacements).

The E-SBAS processing, is capable to estimate linear and non-linear displacement trends, applied for both DS and PS pixels.

Once the date by date displacement measurements (known as high pass components) are carried out, the algorithm performs the estimate of the atmospheric effects. First, the displacement model previously estimated is subtracted date by date, from the interferograms measurements (_dint files). Then the atmospheric correction is performed through the application of an Atmosphere Low Pass filter, this accounts for the spatial distribution of the atmospheric variations. It is implemented by using a square window: large windows are more suitable to correct large scale variations, while small windows are better to correct isolated artifacts due to localized variations. The smaller is the window size, stronger will be the filter effect.

- Atmosphere High Pass, this accounts for the temporal distribution of the atmospheric variations. It is implemented by using a temporal window: large windows are more suitable to correct effects with low temporal variability, while small windows are better to correct frequent atmospheric variations. The bigger is the window size, stronger will be the filter effect.

The displacement values are reported with:

- Positive sign if the movement corresponds to a decrease of the sensor-to-target slant range distance.
- Negative sign if the movement corresponds to an increase of the sensor-to-target slant range distance.

It is worthwhile to mention that the re-flattening, which is performed on the displacement products, does not foresee the orbital refinement; it means than only a ramp (using minimum three GCPs) or a constant term (using minimum one GCP) can be removed.

Input files

Insert the auxiliary.sml file.

Parameters

Leave the default parameters.

Atmosphere Low Pass Size

Enter the window size, in meters, to apply the spatial distribution related filter (refer to the Technical Note).

Atmosphere High Pass Size

Enter the window size, in days, to apply the temporal distribution related filter (refer to the Technical Note).

Rebuild All

By setting this flag the second step of the PS Inversion process is started from scratch.

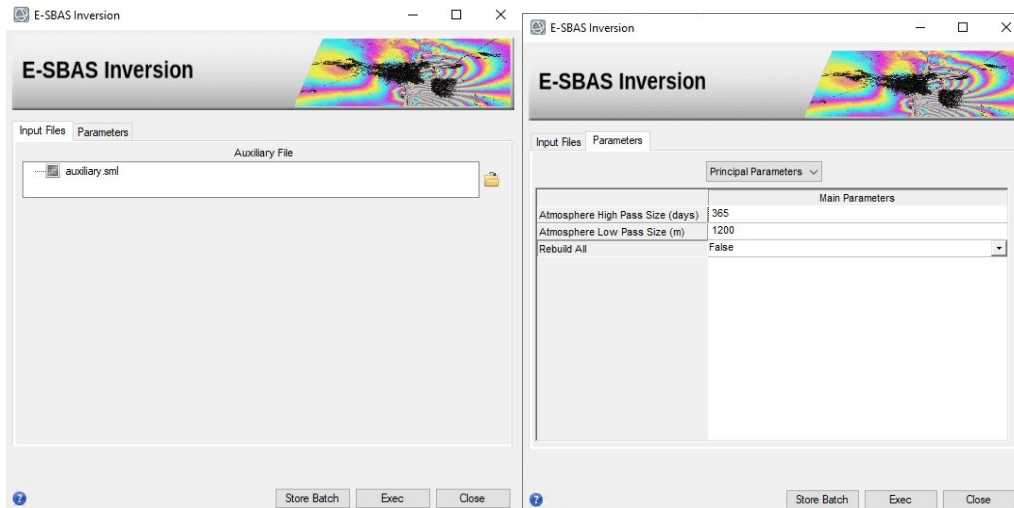


Figure 26 Inversion Step panels for input and parameters.

Output

The **inversion** folder includes:

- **Height**, corresponding to the correction (in meters) with respect to the input Digital Elevation Model, after atmospheric correction.
- **precision_height**, corresponding to the estimate in meters of the residual height measurement average precision (refer to the Phase to Height conversion for more details).
- **Velocity**, corresponding to the mean displacement velocity (in mm/year, after atmospheric correction).
- **precision_vel**, corresponding to the estimate in millimeter/year of the velocity measurement average precision (refer to the Phase to Displacement conversion for more details).
- **cc**, coherence corresponding to the combination of the coherence layers obtained with the PS and SBAS processing method.

Meta files allowing to load the specific processing results (**_meta**).

- **slant_atm_meta**, which refers to date by date atmospheric related components in slant range geometry. This meta file can be found in the working folder.
- **slant_dint_reflat_meta**, which refers to the date by date flattened interferograms, measured in slant range geometry, after the atmospheric correction.
- **slant_disp_meta**, which refers to the date by date displacements, measured in slant range geometry, after the atmospheric correction.

Load the *Velocity* and the *cc* layers and apply the Rainbow color table to the Velocity layer. The mask is retrieved from the SBAS processing, as no thresholds are applied during the E-SBAS processing chain to discard pixels.

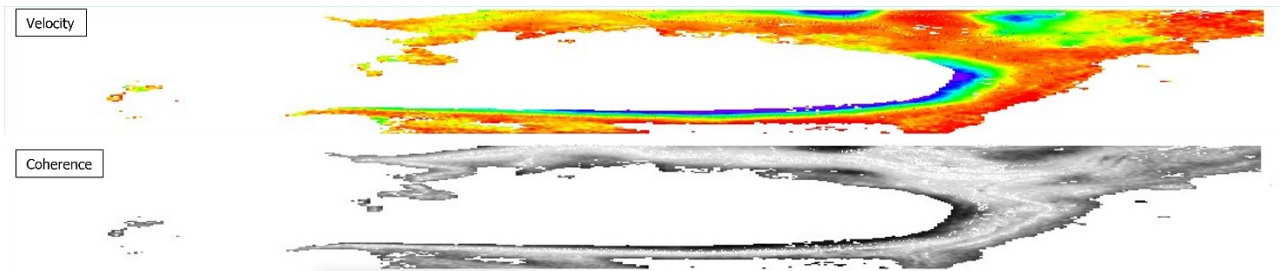


Figure 27 Velocity and coherence layers generated during the Inversion step. The dark areas visible in the coherence layer correspond to low coherence areas, while the brighter ones correspond to areas with higher values of coherence.

The reference layers used to compute the E-SBAS coherence are saved at the following path: *ProjectName_tutorial_ESBAS_processing/work/work_inversion* and corresponds to the following files:

- *cc_hp*: Coherence High Pass, which corresponds to the coherence obtained with the PS approach.
- *cc_lp*: Coherence Low Pass, which corresponds to the coherence obtained with the SBAS approach.

Geocoding

The E-SBAS products are geocoded and the displacements can be displayed in two kind of format: Shape and/or Raster according to the flag selected in the parameters.

Input files

Insert the auxiliary.sml file.

Optional Files

Refinement GCP File

Leave the default parameters.

TIP In order to obtain more accurate displacement measurements, one or more **Ground Control Points** (e.g. coming from GPS or other ground measurements) - "Refinement GCP file" - can be entered as input to the processing. This information is used to **optimize the displacement trend assessment**. In case only one GCP is selected, the correction will consist of a mean velocity constant offset, which does not have any spatial variation. If more GCPs are selected, the correction consists of the best fitting calculated from all GCPs.

The Ground Control Points must be provided in cartographic coordinates. This adjustment is not mandatory.

DEM /Cartographic System

Insert the *aw3d30m_dem* provided in the input dataset.

Parameters

- *PS Coherence Threshold*
Pixels with coherence values smaller than this threshold will be considered as DS, pixels with coherence values higher than this threshold will be classified as PS.
- *PS Coherence Threshold*

Pixels with coherence values smaller than this threshold will be considered as DS, pixels with coherence values higher than this threshold will be classified as PS.

- **Generate KML**
By setting this flag the Google Earth .kml of the resulting ESBAS is/are created. and the Upper/Lower limit of KML scaling parameters are activated
- **Upper Limit KML Scaling**
The maximum expected displacement rate (integer value of the velocity in mm/year) is set (This field is only active if the Generate KML flag is set to True).
- **Lower Limit KML Scaling**
The minimum expected displacement rate (integer value of the velocity in mm/year) is set (This field is only active if the Generate KML flag is set to True).
- **Make Geocoded Raster**
By setting this flag the output raster file/s are generated.
Set it to True.
- **Make Geocoded Shape**
By setting this flag the output shape file/s are generated.
- **Make Slant Shape**
By setting this flag the slant range products are generated in vector format. By default, this option is set to false.
Note: the output shape will be created inside the inversion folder.
- **Rebuild All**
This flag refers to all E-SBAS process. By setting the flag the whole process is performed from scratch (if not incremental mode is active). It is advisable to leave this flag unchecked in case of process interruption, so that the products already generated have not to be computed and stored again.
- **Geoid Type**
EGM96
Earth Gravitational Model 96.
EGM2008
Earth Gravitational Model 2008.
- **Refinement Radius (m)**
Maximum buffer radius for the association of Ground Control Point with respect of the slant range unwrapped phase closer valid pixel.
- **Refinement Residual Phase Poly 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 than 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.
- **Vertical Displacement**
By setting this flag the displacements and velocity products are projected on the vertical direction. Do not use the reprojection if the real displacement direction is unknown.
- **Slope Displacement**
By setting this flag the displacements and velocity products are projected along the maximum slope. Do not use the reprojection if the real displacement direction is unknown or when the reference DEM resolution is poor with respect to the process results.
- **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. Do not use the reprojection if the real displacement direction is unknown.

- **Azimuth Angle**
Custom Direction Azimuth Angle measured in degrees from the North - clockwise direction.
- **Inclination Angle**
Custom Direction Inclination Angle measured in degrees from the horizontal plane.
- **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.

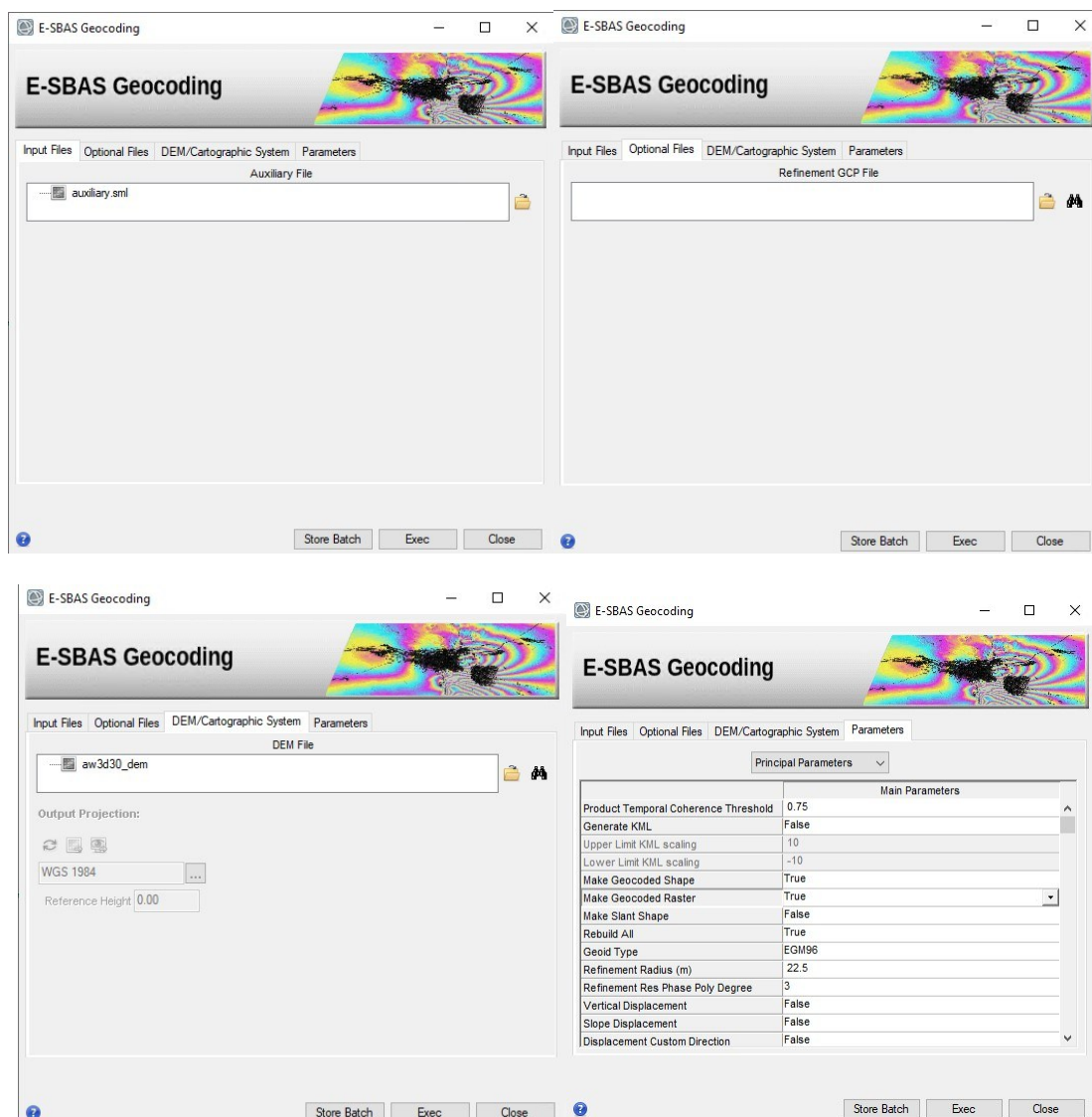


Figure 28 E-SBAS Geocoding panels.

Output

The **geocoding folder** includes:

- .shp: Shapefile of the PSs with the associated files (.shx, .dbf and Google Earth .kml). If the number of points is larger than the "Shape Max Nr of Points" defined in the Persistent Scatterers Parameters several shapefiles are created. The file name is created as follows: *_PS_DS_XX_Y.shp where XX is the decimal part of "Product Coherence Threshold" (0.XX), Y is an incremental number in case of more than one shapefile and * is the output root name chosen in the connection graph step.

Field description of the generated shape file:

- velocity: mean velocity of the displacement for each pixel [mm/y]
 - coherence: multitemporal coherence, it is a quality index for the best fitting of interferometric phase date by date
 - MuSigma: it is a quality index, it is the mean/standard deviation ratio, where mean corresponds to a temporal mean
 - Scatterer: it defines if a point is a PS or a DS
 - Hprecision: estimate of the height measurement average precision [m]. It is computed considering the acquisition spatial baseline, considering the multitemporal coherence
 - Vprecision: estimate of the velocity measurement average precision [mm/year]. It is computed considering the acquisition temporal baseline considering the multitemporal coherence
 - Range: pixel coordinate
 - Azimuth: pixel coordinate
 - SubArea ID: ID of the SubArea
 - lon/lat: geographic coordinates
 - xpos/zpos: cartographic coordinates based on the DEM reference system
 - zpos: corrected elevation (ellipsoid elevation), DEM reference height + Hcorrection
 - Z: corrected geoid height, zpos - Hgeoid
 - ALOS: Line of Sight Incidence angle on azimuth direction
 - ILOS: Line of Sight Incidence angle on vertical direction
 - Hcorrectio: correction with respect to the input Digital Elevation Model [m]
 - D_date: displacement acquisition date in millimeters.
- **ESBAS_disp_geo_XX_meta**
This meta file is created if "Make Geocoded Raster" is selected. It contains three file called *_ESBAS_XX_cc_geo, *_ESBAS_XX_vel_geo, *_ESBAS_XX_height_geo (for coherence, velocity and height residuals). * is the output root name chosen in the connection graph step, while XX is the decimal part of "Product Coherence Threshold" (0.XX). In the meta file the ESBAS_ALOS and ESBAS_ILOS are also included. *_IDdate_XX_disp_geo files, which are the displacement for single dates, are also include; the IDdate identifies each single date image.
 - mean_geo: SAR Intensity average image and associated header files (.sml, .hdr).
 - Ref_GCP_geo, shape file corresponding to the Reference Points of the highest MuSigma values (i.e. those used for the phase offset removal) automatically selected during the step 1

The other raster geocoded files (_vel_geo, _height_geo, _cc_geo et...) are saved under the path _ESBAS_processing\work\work_geocoding.

Time Series Analyzer

A plot, showing the extracted displacement information for a selected PS/DS, can be created using the /SARscape/General Tools/Time Series Analyzer/Vector (in case the Make Geocoded Vector was selected in the Geocoding Step) or /SARscape/General Tools/Time Series Analyzer/Raster Analyzer (in case the Make Geocoded Raster was selected in the Geocoding Step).

TIP The optimal output to be analyzed is the shape file, since it allows exploiting the resolution obtained with the exploitation of PS points. The raster interpolates values and this implies that the resolution of PS points would be lost.

To analyze the displacement time series of a specified PS/DS, load all the *.shp* results as well as the *mean_geo* image in ENVI.

Once a *.shp* is selected in the layer manager, the right click allows to set it as the active layer to display the time series; the Time Series Analyzer/Vector tool can be run.

The data range has to be set in the panel, the Color Apply button allows displaying the data range on the PS/DS shapefile. Once the desired PS/DS is selected, click on "Plot Time Series" in order to open a Plot showing the displacement temporal evolution.

Notes:

- clicking with the secondary mouse button on a different *.shp* file in the Layer Manager and selecting "Set as active layer" allows to change the active layer. This can be done even leaving the SAR TS Vector Analyzer window open.
- depending on the video card, the use of a remote desktop connection does not allow showing different colors on the shapefile. To remedy this limitation, please connect directly at the remote location and reboot the machine or copy the results on a local computer.

TIP In case multiple shp files are created, choose the velocity interval for all the different shapefiles.

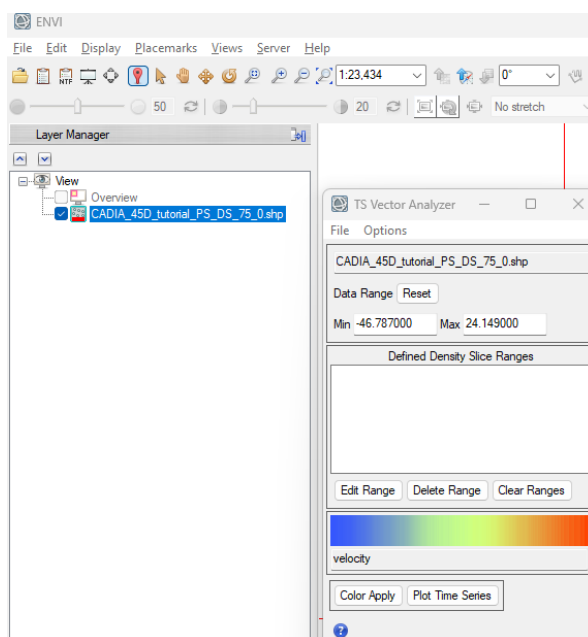


Figure 29 Time Series Panel.

Results

The results of the E-SBAS processing in the Cadia area can be seen in Figure 30. The figure shows as the results are characterized by a widespread stable behavior (green areas). However, blue areas highlight a significant subsidence, mainly affecting the south-west TSF embankment.

The visualization color stretch in the area ranges between -30 mm (blue) and +30 mm (red).

The point on the TSF embankment shows a cumulative displacement of around 100 mm. The time series “jump” visible in the final part of the TS is likely due to an acceleration that occurred in that area of the TSF.

Note that a strong acceleration has been detected starting from December 2017, three months prior the collapse of a part of the TSF embankment.

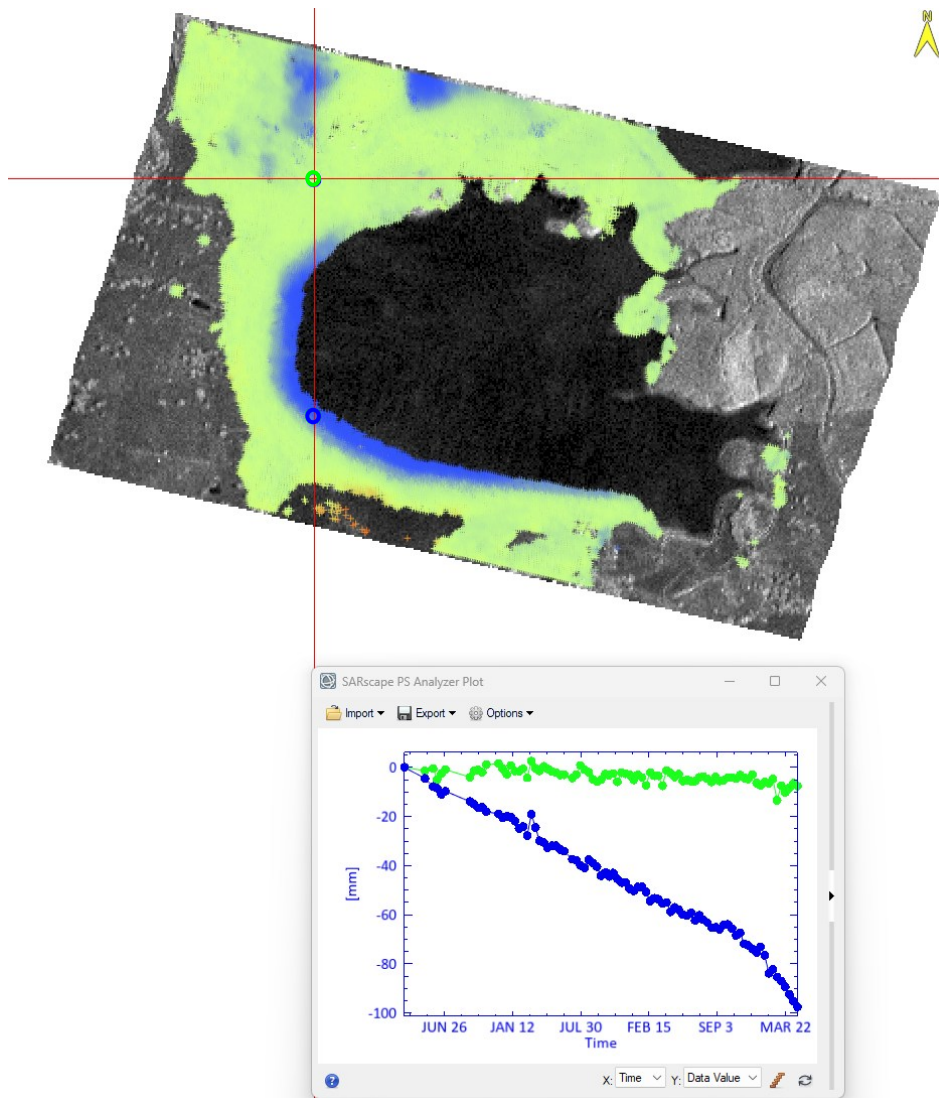


Figure 30 E-SBAS Velocity vector map and Time series plot of the two selected points.

A comparison between the E-SBAS and the SBAS results obtained with the same data stack is shown in Figure 18. The comparison highlights the increase of the detail level in contouring the displacement areas reached

with the E-SBAS technique. This behavior is visible in the blueish moving area located north of the velocity map. This is due to the capability of the E-SBAS technique in including in the final result the PS points too.

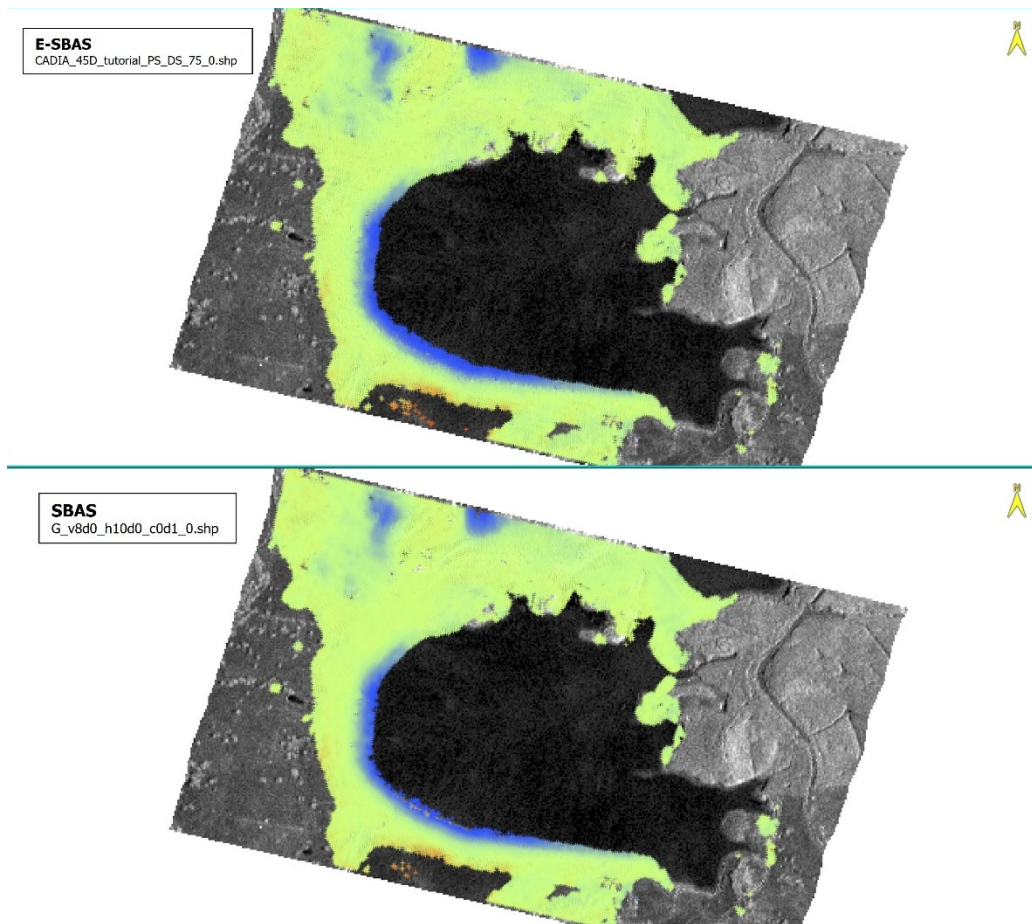


Figure 31 E-SBAS - SBAS vector velocity maps comparison.

The information regarding the number of PS and DS points is contained in the output shape file generated under the path *ProjectName_ESBAS_processing\geocoding*; 7508 PS and 22470 DS points have been retrieved. In Figure 32 PS points are represented in Red, while DS points are represented in blue.

The E-SBAS processing chain generated a total number of 29978 points (considering both PS and DS), while with the SBAS processing a total number of 27829 DS points have been retrieved.

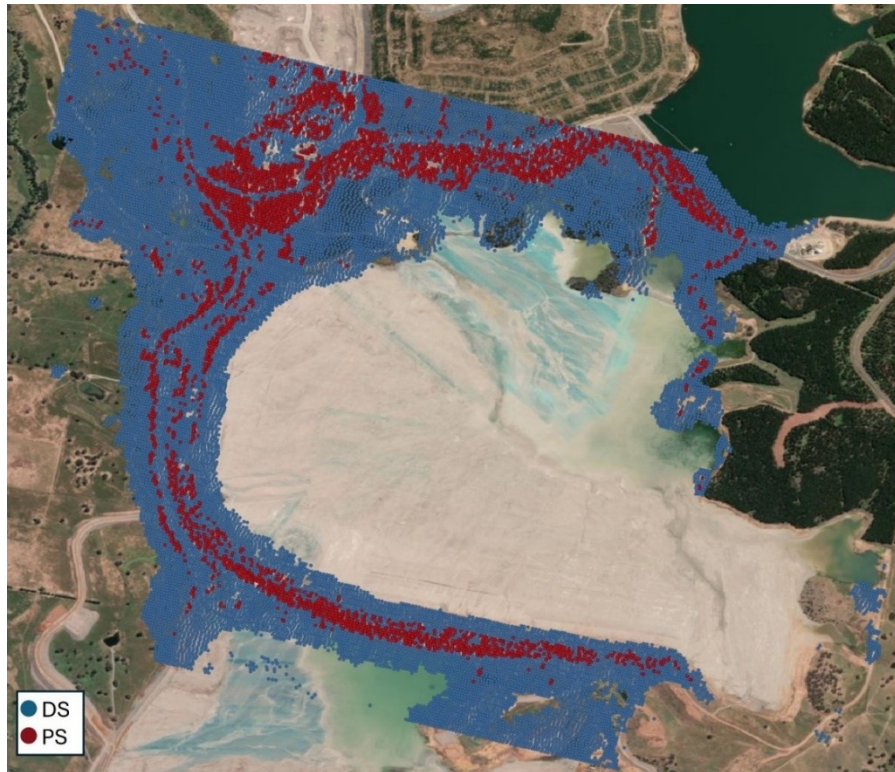


Figure 32 Shape file generated after the geocoding step. PS points are represented in Red, while DS points are represented in blue.

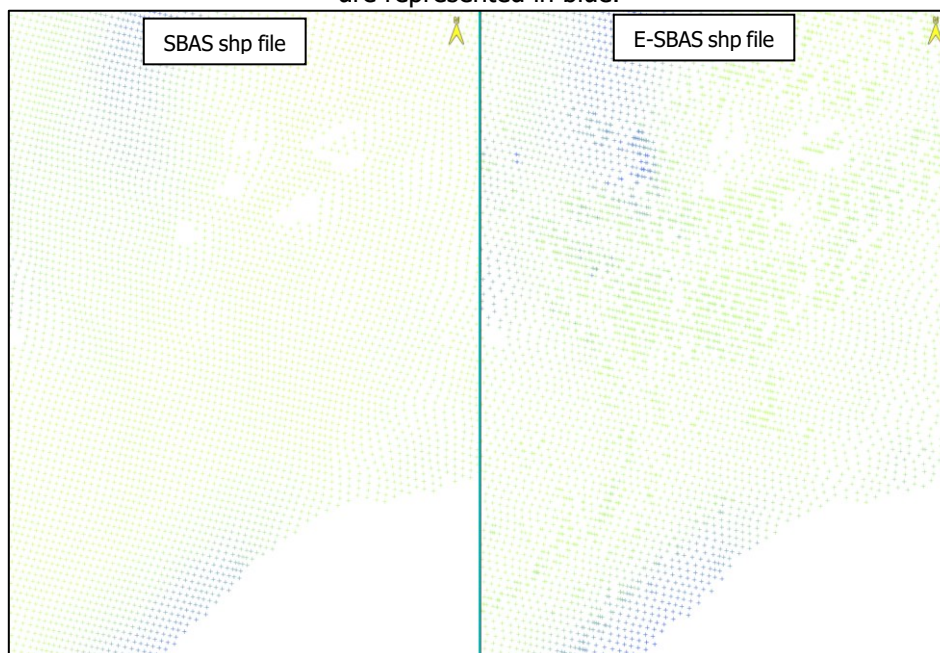


Figure 33 SBAS vs E-SBAS: Shapefile Comparison. DS points are spatially interpolated, which is why the points are represented in a regular grid in the SBAS shapefile. In contrast, the E-SBAS output contains both PS and DS points. PS points are not spatially interpolated, preserving the PS spatial resolution.

NOTE: The results can be further improved by processing a larger AOI and selecting a Refinement GCP located in correspondence of a stable point far from the collapsed area. In this tutorial, a relatively small AOI was used to minimize processing time and facilitate workflow completion.

Annex 1. Auxiliary File

The auxiliary file is used by all stacking interferometry steps. This file is the stacking central thread; it reports the updated list of steps and sub-steps performed so far by the SBAS and its path location describes the internal path folders and sub-folder locations to the software interfaces. In case a step of the stacking interferometry processing is stopped for any reason, the same can be started again and the SBAS will be able to continue from the last processed pair on, without re-starting from scratch. At present time this feature is limited in the cluster version, where only the steps performed are considered, not the single pair counter.

The "Auxiliary file" (auxiliary.xml) is saved in the root output directory and it is updated during the execution of the different processing steps. It is generated by the *Generation Connection Graph* step. It is the input for the *Interferometric Process* step onwards, throughout the whole processing chain; it is important to note that the first input to enter, in any processing panel, is the auxiliary.xml.

TIP To further simplify this procedure, the steps to be executed can be stored in a batch sequence so that it will be very easy to stop them and let them continue again by exploiting the *Batch Browser* tool (see the *Getting Started* tutorial for more information).

It is possible to edit this file when the user decides to perform again a particular operation. For example: while looking at intermediary results, it was discovered that a new tuning of the parameters should be done. To remake a sub-step, the *auxiliary* file must be edited by setting "NotOK" the corresponding sub-step and setting to 0 the relative counters. Once the SBAS step is run again, it will start from the step edited to "NotOK" in the Auxiliary files and will go on, by skipping the previous sub-steps and hence saving time. Consider that the sub-steps are ordered according to their execution sequence. It means that all the following sub-step after the "NotOK" will be performed again.

Example for SBAS: the interferogram generation (and the next steps) must be re-done:

Portion of the Auxiliary as before re-starting:

```
< interf_stack>OK</interf_stack>
< interf_stack_master>20</interf_stack_master>
< interf_stack_slave>0</interf_stack_slave>
```

Same portion after proper editing, that will force the re-execution of the interferogram generation when the tool is re-started:

```
< interf_stack>NotOK</interf_stack>
< interf_stack_master>0</interf_stack_master>
< interf_stack_slave>0</interf_stack_slave>
```

TIP The exact counters of "*interf_stack_master*" and "*interf_stack_slave*" can be retrieved in the CG_report.txt file (_SBAS_processing/connection_graph folder). This Report file contains the list of images to be processed. The processed pair nomenclature is the following: _MasterDate_m_ID_SlaveDate_s_ID. In this way, it is easy to retrieve which are the counters of the pair under analysis by looking at the acquisition dates and/or the acquisition IDs.

TIP In case the user might also decide to run an entire stacking step again, no modification to the auxiliary file is needed. It is possible to run the desired SBAS tool again setting the Rebuild All flag to True.

Annex 2. Meta viewer

Here is described the correct procedure to open, visualize and use a meta file.

Load for example the meta file corresponding to the final E-SBAS displacement time-series results: "ESBAS_disp_geo_meta", located in the "geocoding" E-SBAS folder. The file contains the displacement time series, the average velocity, and other ancillary geocoded layers.

TIP Whenever the user moves the E-SBAS folder location, the meta internal links (used to load the layers in the ENVI viewer) refer to a wrong absolute path and the meta would not be opened. For this reason, there is another meta file (with the same name) directly inside the sub-folders containing the files to be opened (in this case the "raster" sub-folder).

TIP The SBAS meta files are mainly used by the *Time series Analyzer Raster* tool. For a visual check purposes (for example, visual analysis of the unwrapped phase stack) the use of .series files is recommended.

Notice that opening a meta file in ENVI, will cause the automatic RGB visualization of the first 3 bands in the meta list. This coloured map has not a physical meaning, so the operator must remove it from the "Layer manager" column tab (right click of the mouse over the visualized meta layer name): see Figure 34.

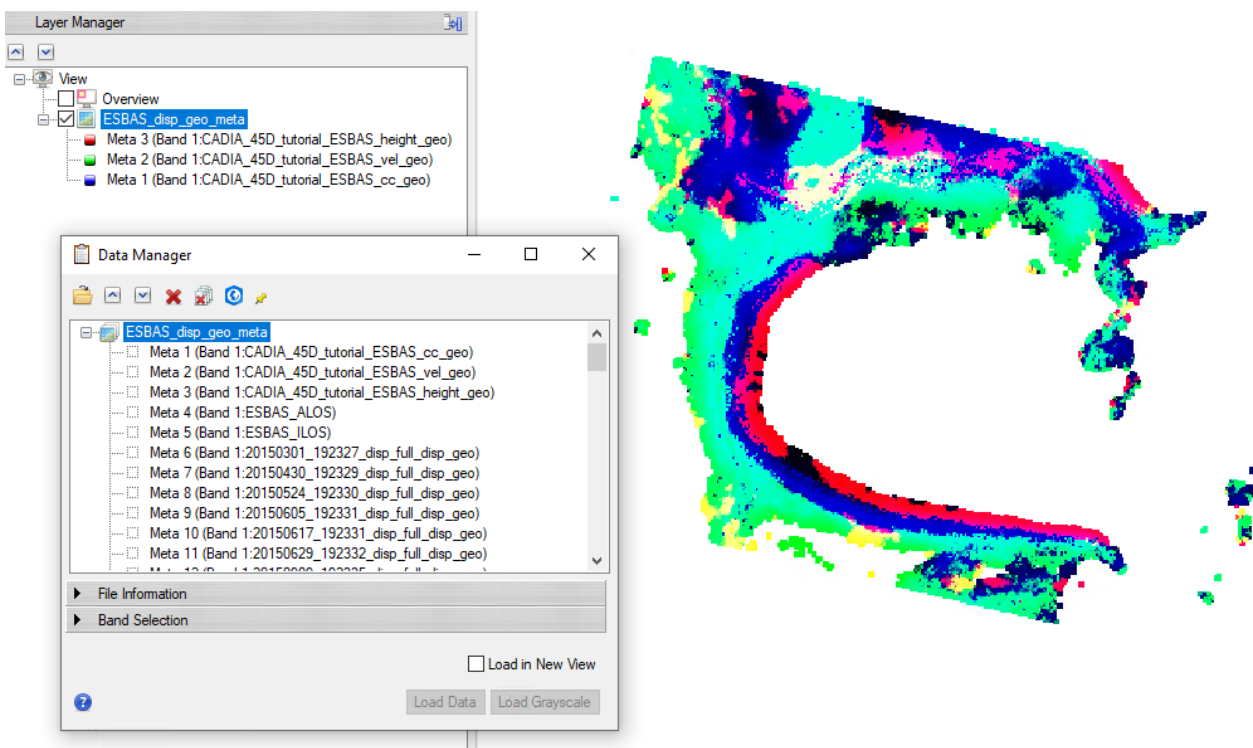


Figure 34 Open "ESBAS_disp_geo_meta" file in ENVI and remove the automatic.

Once the RGB has been removed from the screen, open the Data Manager, and load the desired layer ("_ESBAS_vel_geo") in the ENVI viewer (see Figure 35). Stretch its histogram for a better visualization.

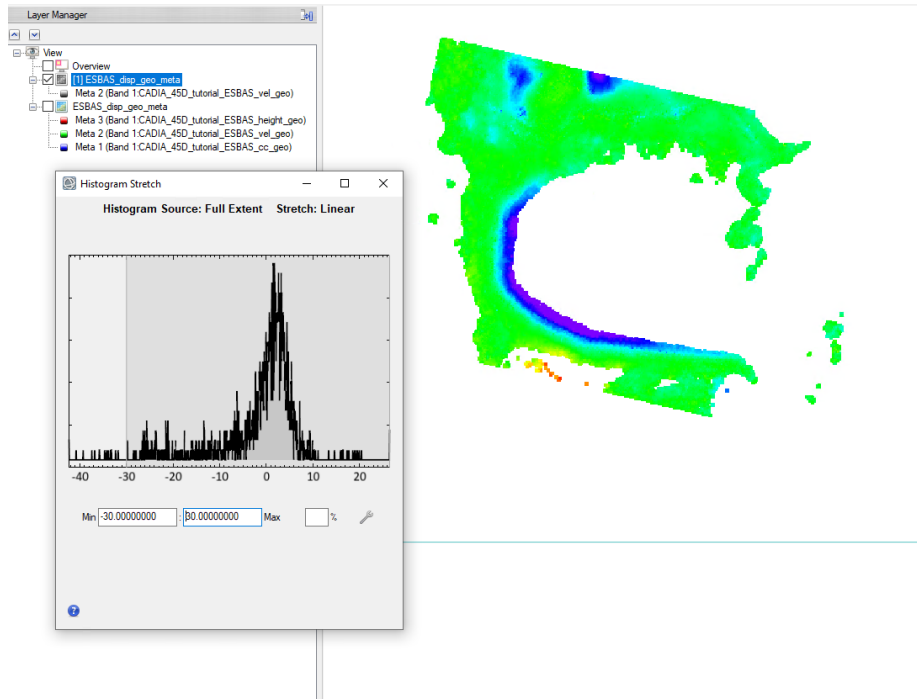


Figure 35 Open “_ESBAS_vel_geo” file in ENVI and correctly stretch between -30 and 30 mm/year.

To visualize the time series (and the ancillary info) for any pixel, just open the */SARscape/General Tools/Time Series Analyzer/Raster* tool and select the meta layer in the “Layer Manager” column tab, click on the desired pixel and plot the time series by clicking “Plot” on the “TS Raster Analyzer” panel (see Figure 36).

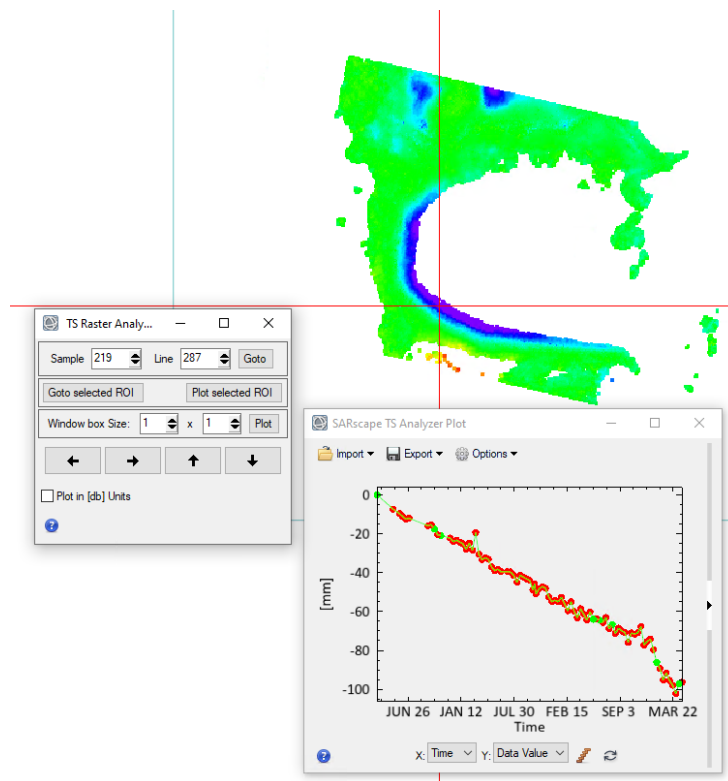


Figure 36 Time series Analyzer Raster.

Annex 4. SBAS Edit Connection Graph

This tool is used to remove or add connections or acquisitions from the SBAS Connection Graph defined by the *Connection Graph Generation* tool.

Note: This tool can be used to edit the connection graph of the SBAS processing only, it can not be used to edit the Connection graph of an E-SBAS processing.

Input files

Insert the auxiliary.sml file.

Principal Parameters

Add Pair

The pair selected in the "Master List" and "Slave List" is added to the original connection network. The process must be re-run from the *Interferometric Process* step. The interferometric pairs already processed in the previous iteration are not generated again; only the new entries will be processed.

Remove Pair

The pair selected in the "Master List" and "Slave List" is removed from the original connection network.

Add Image

The input image list is added to the original connection network. The process must be re-run from the *Interferometric Process* step. The interferometric pairs already processed in the previous iteration are not generated again; only the new entries will be processed.

Remove Image

The image selected in the "Master List" or "Slave List" is removed from the original connection network.

Automatic

The remove pair editing is done automatically accordingly with the Edit Reject Automatic Strong Discontinuities (%), Edit Reject Automatic High Std (%) and Edit Reject Automatic Poor Coverage (%) parameters. The reject and keep stacks meta/series are generated to visually check the automatic editing behavior. The corresponding last processed unwrapped meta/series is updated as well.

Edit Reject Automatic Strong Discontinuities (%)

By setting a reject threshold higher than zero and clicking the *Automatic button* of the SBAS Edit Connection Graph panel, the worst interferograms (a percentage of the whole interferogram stack) are discarded from the stack. The metric for the unwrapping interferogram sorting is the number of wrong discontinuity phase cycles with respect to the number of valid pixels.

Edit Reject Automatic High Std (%)

By setting a reject threshold higher than zero and clicking the *Automatic button* of the SBAS Edit Connection Graph panel, the worst interferograms (a percentage of the whole interferogram stack) are discarded from the stack. The corresponding last processed unwrapped meta/series is updated as well. The metric for the unwrapping interferogram sorting is the unwrapped phase standard deviation.

Edit Reject Automatic Poor Coverage (%)

By setting a reject threshold higher than zero and clicking the *Automatic button* of the SBAS Edit Connection Graph panel, the worst interferograms (a percentage of the whole interferogram stack) are discarded from the stack. The corresponding last processed unwrapped meta/series is updated as well. The metric for the unwrapping interferogram sorting is the valid pixels coverage.

By adding connections or acquisitions, it will start an **Incremental Mode** process: the previous interferograms will be preserved, while the new ones will have to be generated. For this reason, the incremental mode requires the user to run again from the *Interferometric Process* step onward, as evidenced by the pop-up displayed.

TIP It is good practice to store the processing steps in the *Batch Browser* to process new interferograms with the same parameters as those previously made. Eventually the user can find the parameters previously used in the file `"_SBAS_processing\work\work_parameters.sm"`.

TIP Remember that if the user goes through the *Connection Graph Generation* step, the whole old process will be lost, thus losing the benefit of using incremental processing.

This tool can be used whenever the user decides to remove one acquisition, or more frequently some pairs that have been considered incorrectly unwrapped (e.g., after the *Interferometric Process* step or after the *Inversion First* step) or characterized by a low spatial coverage. This editing is finalized to obtain a better result from the SBAS inversions, starting from less but more coherent input unwrapped interferograms. This tool should be used after the unwrapped phase image stack visual check. The pairs to be discarded can be manually identified by opening the corresponding ".series" file as shown in figure Figure 37

Typically, the main reasons to discard an interferogram are the followings:

- Poor coverage due to the low coherence characterizing the interferometric pair (phenological changes, snow coverage, etc.)
- Spatial phase discontinuities caused by the limit of unwrapping tool (fringe aliasing, poor coherence, etc.)

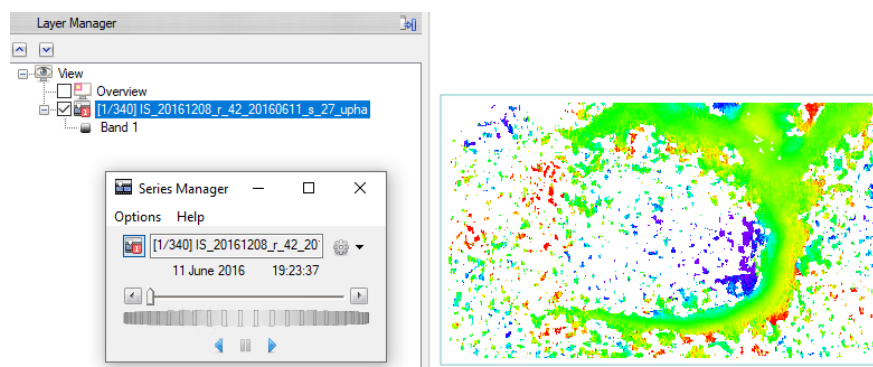


Figure 37 Unwrapped phase series ("`_SBAS_processing\interferogram_stacking\IS_upha.series`") with RAINBOW colored scale.

To select the pairs-connections to be removed, just select the master and one or more slaves, and click on the *Remove pair* button, as shown in Figure 38. The software will check if the operation can be performed, depending on the graph connectivity (*Allow disconnected Blocks* option activated or not) and on the Super Master requirements (the Super Master cannot be removed and must have at least one connection). It is up to the user to decide which method is easier to identify the connections: by looking at the acquisition dates of master and slave, or at their ID (`xx_m_ID__s_ID_`).

No interferograms should be removed in this tutorial because no relevant lack of coverage or unwrapped phase discontinuities are identified. Only as an example of use of the tool we remove the following interferogram: master 18 - slave 12.

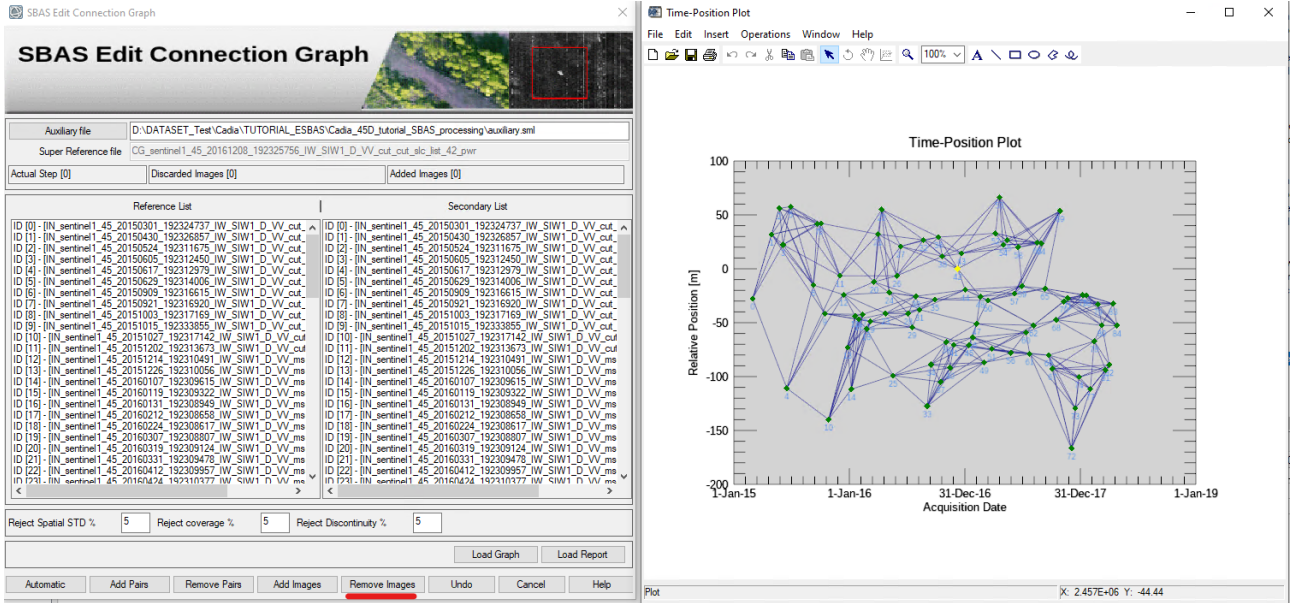


Figure 38 SBAS Edit Connection Graph dedicated tool.

The actual editing step and the number of added and discarded acquisitions are reported in the panel. An acquisition can be discarded because explicitly removed or because all its connections have been removed.

TIP It is recommended to remove not more than 20% of the starting interferometric stack in order not to reduce too much system redundancy.

Annex 5. Refinement and Re-Flattening

Automatic Refinement and Re-flattening – Available from version 5.6.2

The refinement and re-flattening are automatically performed at the beginning of the “Inversion: First Step”, the “Inversion: Second Step” and the “Geocoding” steps. These operations are performed before the inversions to estimate and remove the remaining offsets and ramps from the ingested unwrapped phase stack and final calibration is applied to the slant range products (velocity, height and displacement) during the geocoding step.

The goal of the automatic Refinement and Re-Flattening, for the first and second inversion, is the definition of the stable areas. The algorithm will use the coherence, mu-sigma, modeled displacement rate and residual topography layers to define stable areas, with high coherence and small residual topography; a different mask file will be created for each inversion; the files is located within the work folder of the first and second inversion (*project_name_SBAS_processing/work/.....inversion*):

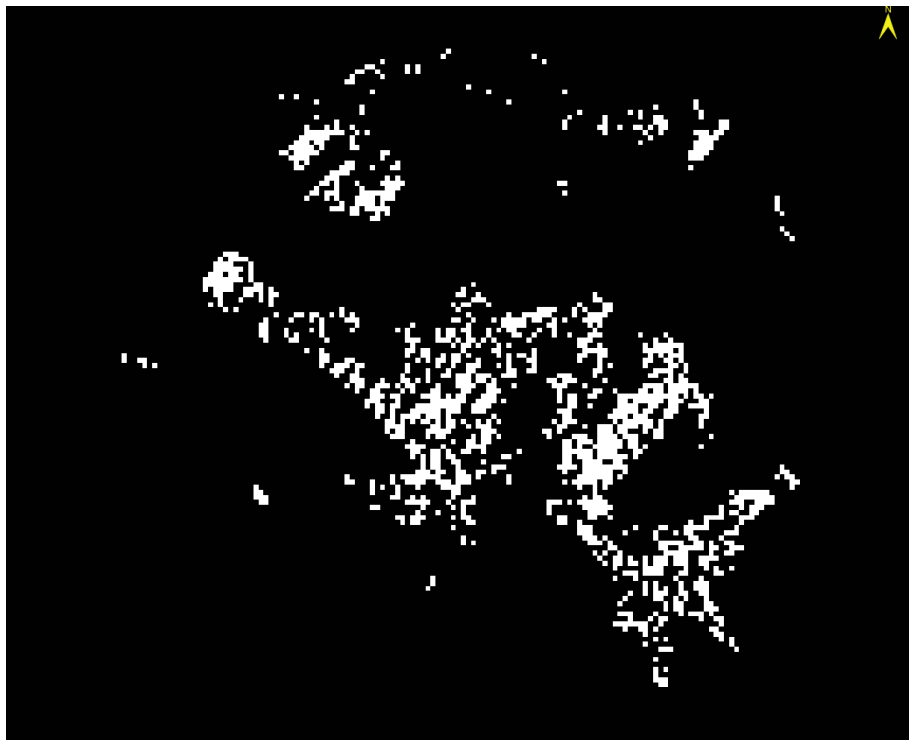


Figure 39 Stable areas mask

(*project_name_SBAS_processing/work/work_first_inversionFI_initial_refinement_mask*)

The created mask is applied to each unwrapped interferogram in order to select valid GCPs according to the coverage of the single interferogram.

In the **first inversion** the ingested unwrapped interferogram stack must be reflattened to remove residual phase offset and trends. The stable areas mask is defined iteratively based on the results of the first inversion itself.

In the **second inversion** the ingested second unwrapped interferogram stack must be reflattened to remove residual phase offset and trends that could have been introduced by the unwrapping algorithm; see chapter 8. *SBAS - Inversion: Second Step* for more details. The stable areas mask is improved based on the results of the first inversion:

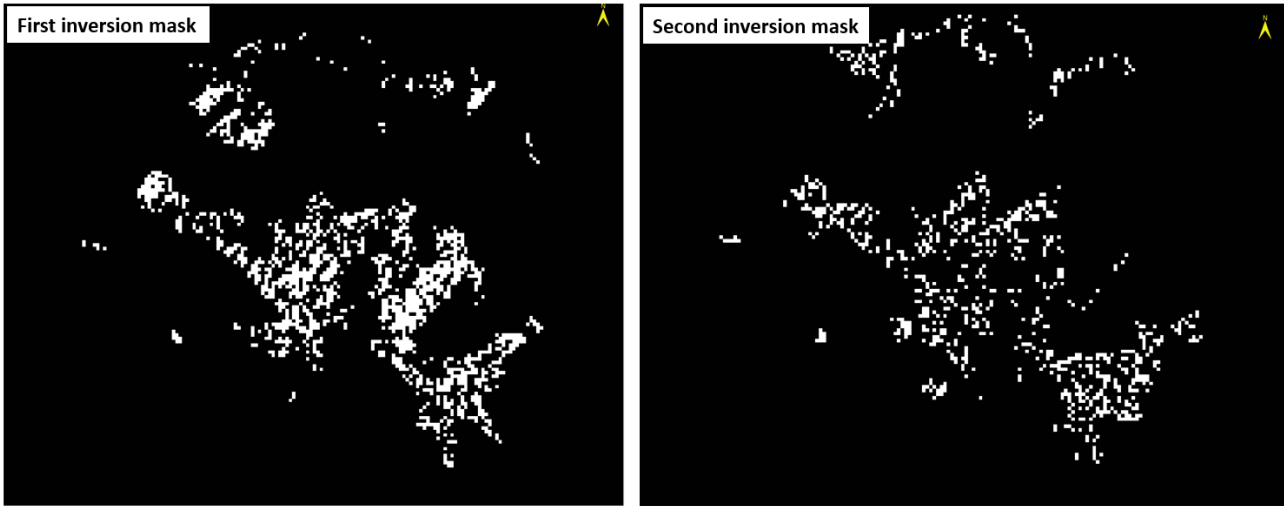


Figure 40 Comparison between the first and second inversion mask.

The final Reference Point is generated during the geocoding process and it is applied on the final slant range products (velocity, height and displacement); this point is characterized by zero displacement and zero residual topography, all the pixels within the area of interest will be calibrated to this final GCP. This point is saved in the geocoding folder of the SBAS processing folder (*project_name_SBAS_processing/geocoding/G_refinement_GCP.km*):

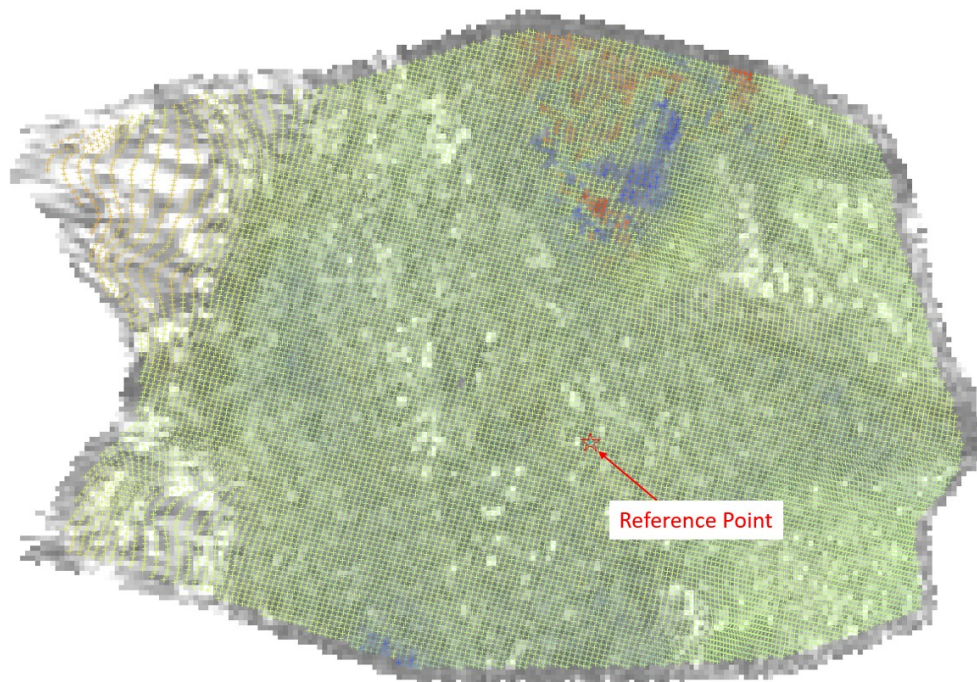


Figure 41 Reference Point location

Manual Refinement and Re-flattening

The user can decide to run the Refinement and Re-flattening manually by inserting the optional Ground Control Points (GCP) in the "Refinement GCP file" or let the software create masks to automatically identify which areas are stable and without residual topography (as described in the previous section). In this annex we add some details to the tutorial dedicated to the creation of GCPs (see the Tutorial "Ground Control Point"), oriented to the SBAS processing.

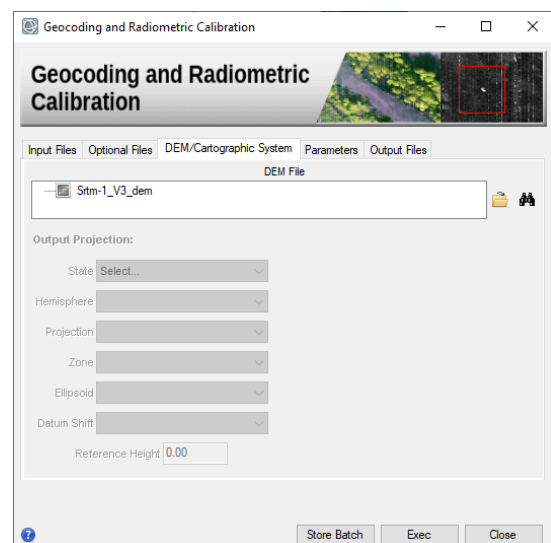
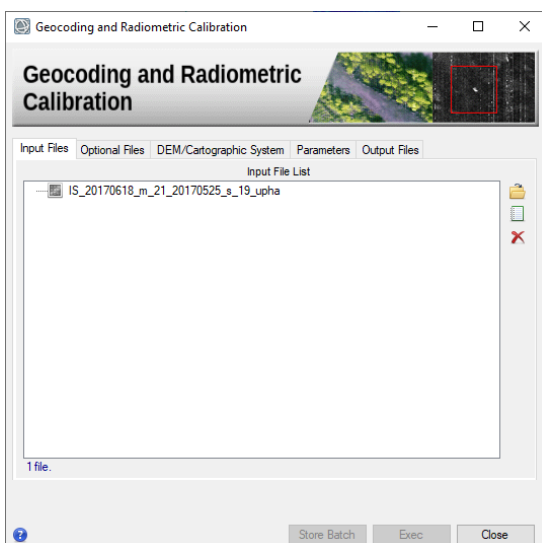
The GCP for refinement can be selected both in slant range geometry and in geocoded geometry and can be unique for all SBAS steps that require it.

The location of the GCPs should respect some general criteria (see the Tutorial "Ground Control Point") applied to most of the ingested unwrapped interferograms or to the slant range products. It is suggested to select a representative image, during the analysis of the unwrapped interferograms stack or slant range products, in terms of coverage (pixels over coherence threshold) and stable areas identification capability.

It is difficult to find the perfect set of points that can work in the same way for all pairs, having different coverage given by the different coherence values. For this reason, it is suggested to introduce many points (at least 20-30) well distributed. In this way, it is more likely that almost all the interferograms will be well re-flattened and, above all, that all unwrapped interferograms match at least one GCP in a valid position (where the coherence is above threshold).

TIP The GCPs are generally chosen in slant ranges, but if they are used as common anchor points between several datasets (different sensors or different acquisition geometries), they must be generated in a common geocoded geometry. The software that will automatically reproject the points from the geocoded geometry to the corresponding slant range geometry in use. The dataset in descending geometry of this tutorial has been designed to be used in combination with the ascending geometry, and it is in this perspective that we have decided to generate the points in geocoded geometry.

To generate the GCPs in the geocoded geometry: choose one or two representatives unwrapped interferograms (or slant range product such as the "SI_velocity" layer) from each available processed stack (in this tutorial only one interferogram will be taken) and geocode them using the dedicated *Geocoding and Radiometric Calibration* tool found in the basic module. These will be the references to define the position of the GCPs.



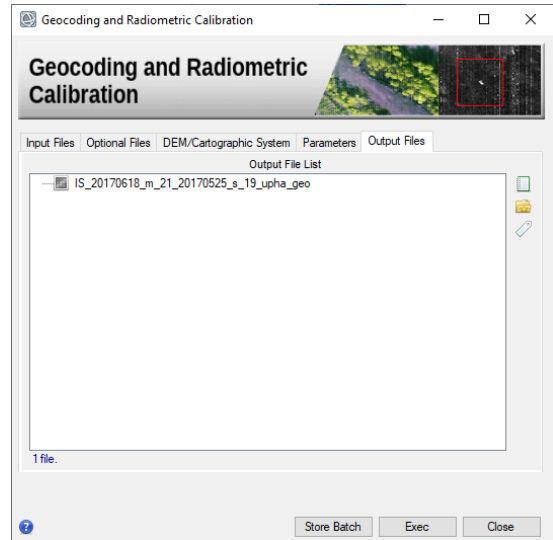
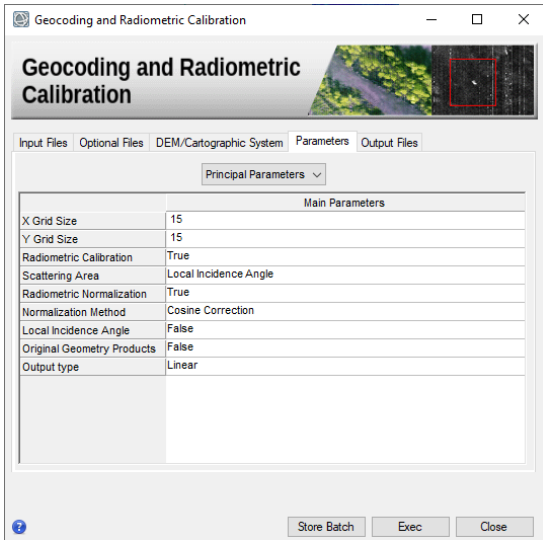


Figure 42 Panels to geocode a representative unwrapped interferogram.

Once the reference layers have been geocoded, proceed with the generation of the GCP file using the dedicated workflow (see Figure 43).

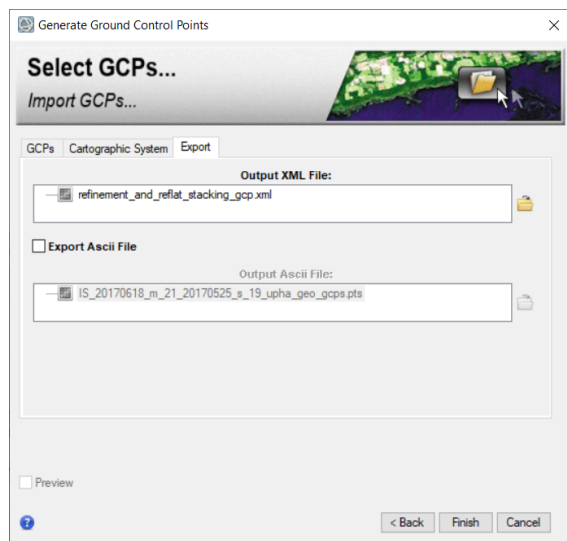
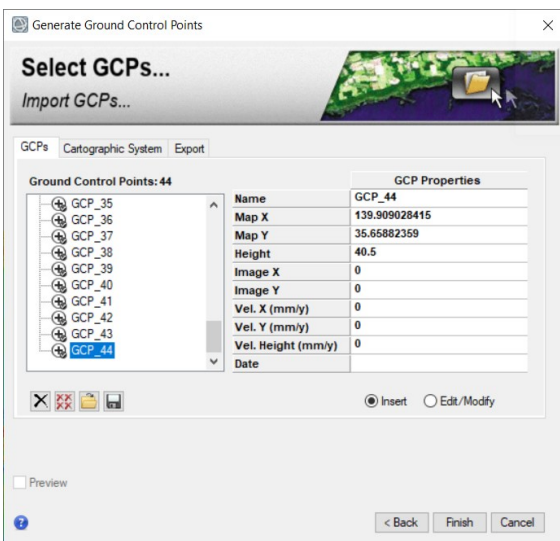
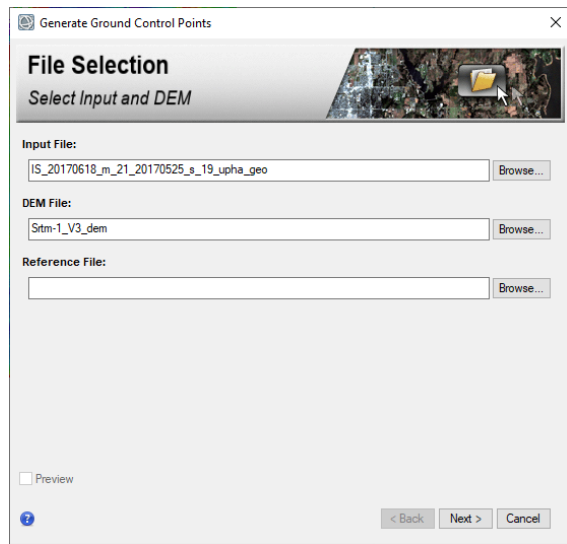
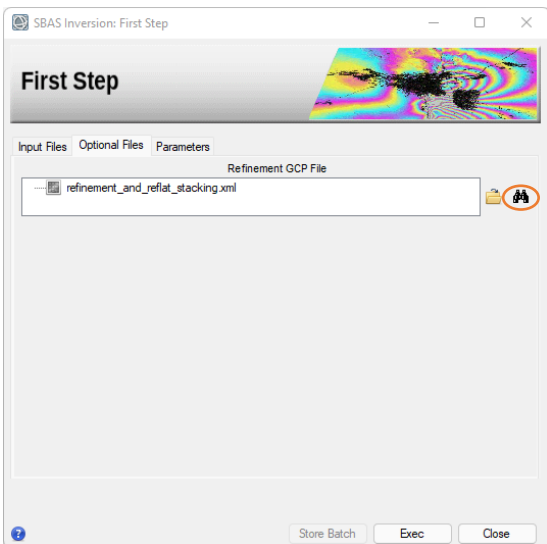


Figure 43 *Generate Ground Control Points* GCP selection workflow. This interface can be accessed from the binoculars button or directly from the dedicated tool in *the General Tool* menu section.

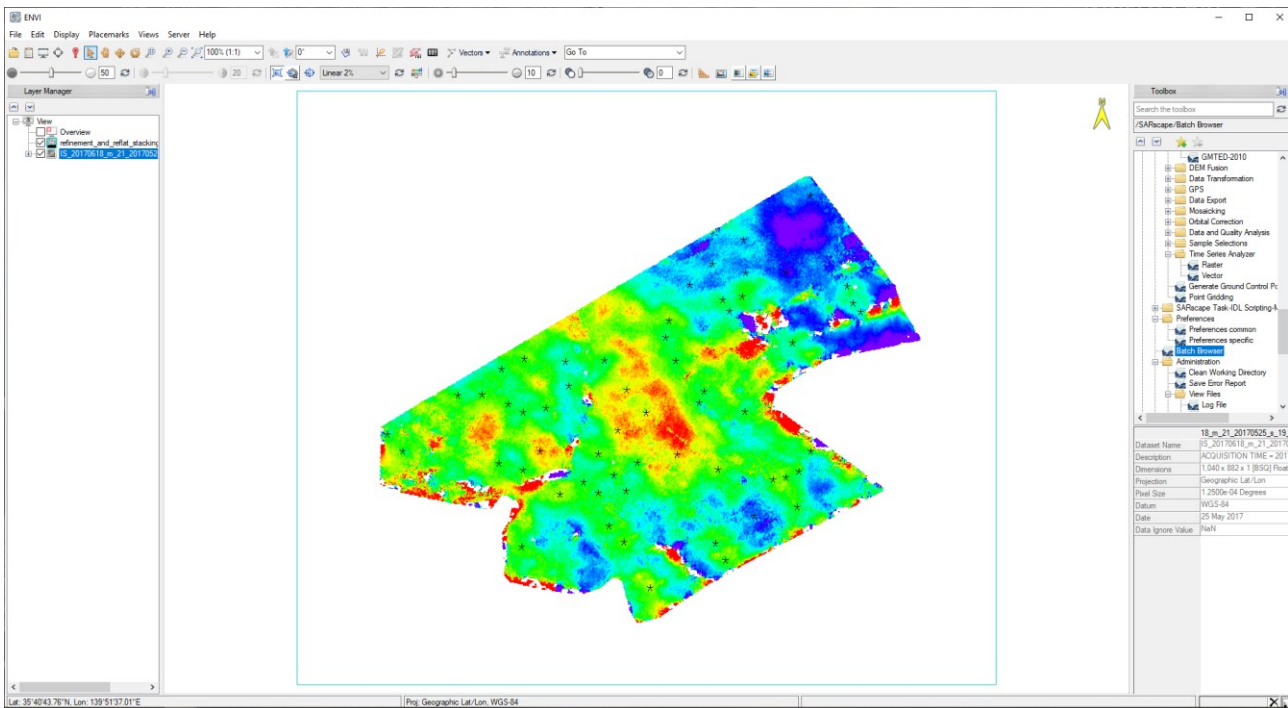


Figure 44 GCP (shape) position in geocoded geometry over coherent areas (above the coherence threshold) and over probably stable points.

Output

The corresponding processing folder includes the following products:

- *_refinement_GCP.xml*, which is a copy of the input refinement GCPs used.
- *_refinement_GCP.kml*, which is a Google Earth visible version of the input refinement GCPs used.
- *_refinement_GCP_geo.shp*, which is a slant range shape version of the input refinement GCPs used.
- *_refinement_GCP_slant.shp*, which is a slant range shape version of the input refinement GCPs used.

Generated meta and series files:

- *_reflat_fint_meta*, *_reflat_fint.series*, which refers to all re-flattened wrapped interferograms.
- *_reflat_upha_meta*, *_reflat_upha.series*, which refers to all re-flattened unwrapped phases.
- *_reflat_*, which refers to all slant range re-flattened products.

TIP It is very important to check the re-flattened unwrap phases and the re-flattened slant range products detecting the residual inaccurate orbits ramp which may require a better positioning of the refinement GCPs.

References

Parizzi, Alessandro, Ramon Brcic, and Francesco De Zan. "InSAR Performance for Large-Scale Deformation Measurement." IEEE Transactions on Geoscience and Remote Sensing (2020).

Larsen, Y., et al. "European Ground Motion Service: Service Implementation Plan and Product Specification Document." Report to CLMS, ver 1 (2020).

Cressie, Noel. Statistics for spatial data. John Wiley & Sons, 2015.