Enhanced-PS Tutorial

SARscape Version 6.1.0

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Contents

Introduction

The main goal of this tutorial is to give a general description of the SARscape Enhanced-PS (EPS) processing chain to obtain the temporal evolution of surface deformations affecting both Persistent Scatterers and Distributed Scatterers.

The proposed approach for E-PS is inspired by Ferretti (2011) and Fornaro (2015). The joint processing of PS and DS can be carried out independently, without the need for significant changes in the standard PS processing chain. This approach aims to extend the standard PS analysis to rural areas.

The E-PS technique is based on:

- the identification of **point targets** (single pixels or group of pixels) which are **radiometrically stable in time**. The point targets are characterized by strong reflection (high backscatter) and high coherence in the observation period. Radiometrically stable targets are urban infrastructures (buildings, bridges, greenhouses, dams, metallic features, etc.) or natural objects (outcrops, exposed rocks etc.).
- the availability of a **high number of input images** for the pixel coherence estimation. The larger the number of acquisitions the better the reliability and quality of the measured PS deformation (in terms of displacement and velocity) and their temporal evolution. A minimum of 20 acquisitions are needed to perform PS analysis to obtain reliable results (A. Ferretti, C. Prati and F. Rocca: "Permanent scatterers in SAR interferometry". Geoscience and Remote Sensing, IEEE Transactions on, vol. 39, no. 1, Jan. 2001, pp. 8 - 20).
- the **linear model** used as assumption to derive the estimate deformations. Non-linearity can be detected if the displacement between two consecutive acquisitions does not exceed $\lambda/4$.

Basically, the PS techniques, identifying point targets radiometrically stable in time, allows the estimation of the residual height and displacement of the persistent scatterers in analysis: The estimates are based on a linear regression.

The new E-PS approach, thanks to the application of an adaptive filter on the interferometric phase, introduces the following key features while retaining the characteristics of the original PS technique:

- The ability to identify temporally disconnected coherent targets, such as rural areas, snow coverage variation, and low-vegetation areas, which considerably increases coverage.
- The ability to obtain less noisy displacement time series for permanent scatterers.

More in detail, two main steps are needed: first, the identification of ensembles of pixels that are similar from a statistical point of view must be performed. The Kolmogorov-Smirnov (KS) and Anderson–Darling (AD) tests are both based on the amplitude of the coregistered and calibrated stack of SAR data. The KS algorithm is simple and effective, but it can present poor sensitivity to deviations in the pixels under test. Indeed, compared to KS, AD puts more weight on the tails of the distributions but at the cost of more expensive computation. Second, for all the DS identified by statistical tests, the covariance matrix, taking advantage of the ensemble of similar pixels, is estimated. SLC phases corresponding to DS are weighed in an optimal way, either by the maximum likelihood estimator (MLE) under the assumption of Gaussianity, or by exploiting the largest principal component of the covariance matrix. DS exhibiting coherence higher than a certain threshold are jointly processed with the PS for the final estimation of the displacement time series.

The following basic requirements have to be fulfilled in the input data series:

- All data must be acquired by the same sensor.
- All data must be acquired with the same viewing geometry.
- In case of multi-polarization acquisitions, the same polarization must be selected for all data.

Workflow Overview

The E-PS technique uses the input slc data to select the pair combination for the interferogram generation. The Reference image is automatically chosen among the input acquisitions while all the other inputs are considered as Slaves. The Reference is the reference image of the whole processing, and all the processed slant range slaves are co-registered on this reference geometry (**Coregistration**). This involves an oversampling factor that is automatically selected based on the acquisition sensor (the oversampling is executed to avoid aliasing of fast fringes in case of large baseline values). Once the Coregistration is performed, the interferograms are generated for each Secondary always using the Reference image (**Interferogram Generation**). The interferometric phase is the contribution of 4 components: the topographic component, the change component, the displacement component and the atmosphere component. It is worth noticing that the spectral shift and the common Doppler bandwidth filters are not executed, as usual in the SAR Interferometry. The input reference Digital Elevation Model is used to perform the **interferogram flattening** and remove the flat earth. The better the reference Digital Elevation Model accuracy/resolution the better the result in terms of **topography removal**. The availability of Ground Control Points for the area allows the correction of orbit inaccuracy for the Master image, performing the manual orbital correction or the automatic orbital correction (typical behavior of sensor like ERS).

Since the PS technique is based on the identification of stable backscatter **the time series of each pixel** are considered, the approach differs from the conventional approaches that process the input scene as a whole.

Once the interferograms are generated, an **adaptive filter** is applied to retrieve both **PS** and **DS**. To achieve this purpose two main steps are required. Firstly, the identification of statistically similar pixel ensembles must be conducted. This involves utilizing the Kolmogorov-Smirnov (KS) and Anderson-Darling (AD) tests based on the amplitude of a co-registered and calibrated stack of SAR data. Secondly, for all DS identified through the statistical tests, the covariance matrix is estimated by leveraging the ensemble of similar pixels. The SLC phases corresponding to DS are optimally weighted using either the maximum likelihood estimator (MLE) under the assumption of Gaussianity, or by exploiting the largest principal component of the covariance matrix. DS exhibiting a coherence higher than a specified threshold are jointly processed with PS for the final estimation of the displacement time series.

Then during the **First Inversion** step the velocity [V'] and residual height [H'] component extraction is performed, using specific range values of these two variables. The "First" term refers to a preliminary inversion, which does not consider the atmospheric delay, which is estimated in the second inversion. To determine V' and H', SARscape automatically considers a stable ground control point (V' and H' equal to 0). The selection of the stable ground control point is based on the identification of a defined number of candidates (by default 5 in SARscape). The candidate's selection is based on the Amplitude Dispersion Index (D), which is defined as

$$D = \frac{\mu}{\sigma}$$

Where μ is the temporal amplitude mean value for the single pixel and σ is the temporal standard deviation. Once the candidates are identified, for each one of them H', V' and temporal coherence are computed. The candidate restituting the highest temporal coherence is selected as the stable ground control point.

Once the Reference Points are identified, a **linear model** is used to estimate the residual height (H') and displacement velocity (V') from all the re-flattened interferograms and H' and V' are computed for each pixel.

The number of the 'Reference Points' depends on the size of the Area of Interest. By default, just **one 'Reference Point'** is selected for areas within 25 km^2.

Considering the area of analysis, the algorithm follows two approaches:

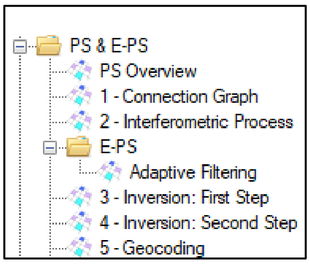
- Areas of analysis with size within the value specified by the 'SubArea for Single Reference Point' parameter: just one 'Reference point' is used to process the entire Area.
- Areas of analysis larger than the value specified by the 'SubArea for Single Reference Point' (by default size larger than 25 km^2): the entire area is split into more sub-areas; the subArea percentage overlap is considered (Overlap for SubAreas [%]). Every subarea is independently processed. A mosaicking process is carried out to merge all the sub-areas results. The merging process is carried out considering a **Super Reference Point** which is characterized by the highest D among the others. The Reference points are used for the phase offset removal.

The velocity, height, coherence and displacements are computed without atmospheric compensation.

The atmospheric component has high spatial correlation and low temporal correlation, to estimate the atmospheric effect, the **Second Inversion** is performed. In fact, once the atmospheric effect is performed, the residual heights and the displacement for each pixel are finally re-computed.

The PS processing is performed in slant range geometry. To be able to analyze and display the PS and DS results in geographic coordinates, the E-PS output is generated in the **Geocoding** step.

The E-PS steps and relative sub-steps are described in the list below and correspond to the workflow shown in the Figure 2 below:



1. Connection Graph Generation
2. Interferometric Workflow
   2.1. Co-registration
   2.2. Interferograms generation and Flattening
3. **Adaptive Filtering (mandatory to compute E-PS)**
4. Inversion First Step
   4.1. Mean power image and Amplitude dispersion index generation (MuSigma)
   4.2. Coherence, velocity and residual topography estimation
5. Inversion Second Step
   5.1. Atmosphere pattern removal
   5.2. Coherence, velocity and residual topography estimation
   5.3. Displacement component estimation
6. Geocoding
   6.1. Coherence, velocity and residual topography geocoded results
   6.2. Displacement geocoding

The step 1,2,4,5 and 6 are in common with the PS processing. To perform an E-PS workflow it is mandatory to run the “Adaptive Filtering” step after the Interferometric Process.

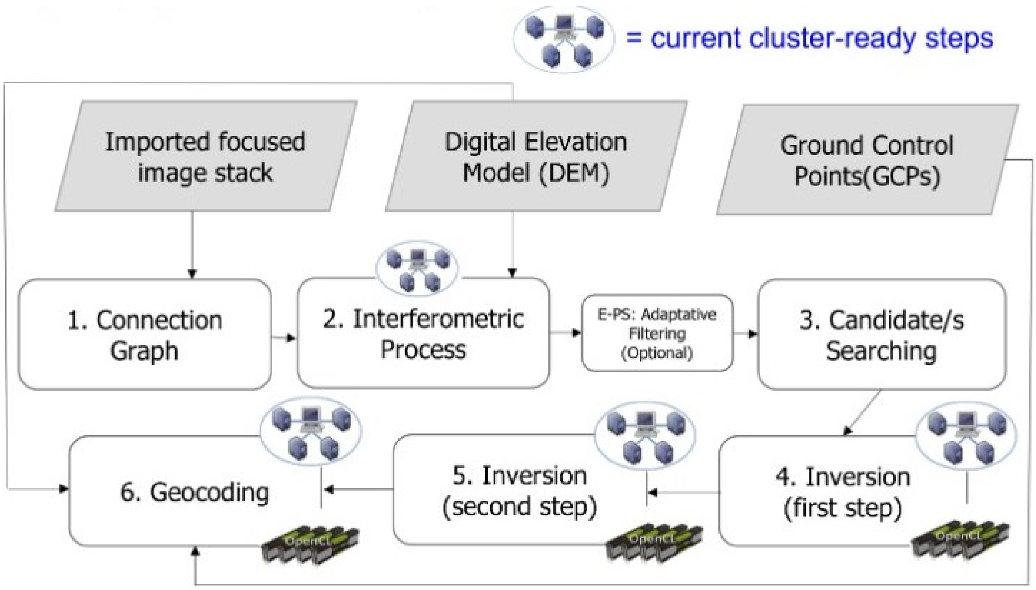


Figure 1 E-PS block diagram.

The steps 1,2,4,5 and 6 are in common with the PS processing. To perform an E-PS workflow it is mandatory to run the "Adaptive Filtering" step after the Interferometric Process.

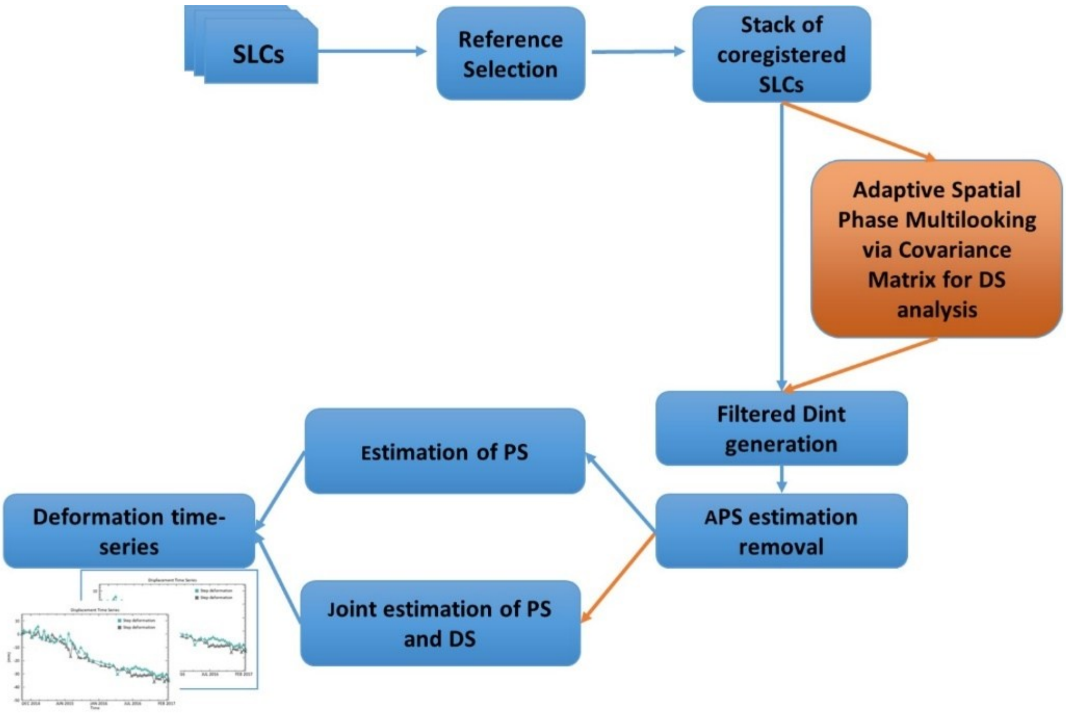


Figure 2 Logical workflow for the E-PS module.

The E-PS 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	64 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 E-PS results shown in this tutorial can be found in the DataSetsTutorials folder on our 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.

Training Data sets description

The training dataset concerns the tailings dam collapse that 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 79 images in VV polarization will be used, the temporal coverage is from the 1st of March 2015 to the 25th of February 2018.

To obtain the 2D displacement projected along the vertical and east-west direction, the E-PS 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 track 45.

Figure 4 Cadia AOI.

Processing Time

The Table below summarizes the processing time to perform the E-PS 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's time required to analyze each step results is not reported since it depends on the user knowledge and experience in E-PS processing.

Step	Time [min]
Connection Graph	1
Interferometric Process	22
Adaptive Filtering	8
Inversion: First Step	3
Inversion: Second Step	3
Geocoding	1

Before starting

Before starting the PS 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 Tutorial to be familiar with the basic processing chain that allows managing the dataset provided to run the PS processing.

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

The binary raster files provided 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).

To quickly analyze the results of each step, SARscape stores each output in the corresponding sub-folders. In fact, once the Connection Graph step is performed, the "(Output Root Name) +_PS processing" folder is created.

The sub-folders are:

- connection graph
- interferogram_stacking
- first inversion
- second_inversion
- geocoding
- work

Connection Graph

This functionality defines the SAR pair combination (Master and Slaves) and connection network, which is used for the generation of 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.

TIP

The connection graph can be edited using the specific tool in SARscape/Interferometric Stacking/Stacking Tools/PS Edit Connection Graph.

The Connection Graph is performed running the SARscape/Interferometric Stacking/PS/1 - Connection Graph panel (Figure 5).

Input files

Insert all the _slc files in the Input file list tab from the "45D_cut" folder of the provided input dataset.

Optional file

Leave the Input Reference file empty (The best possible Reference image will be automatically chosen by SARscape).

Output Files

Choose 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) +_EPS_processing".

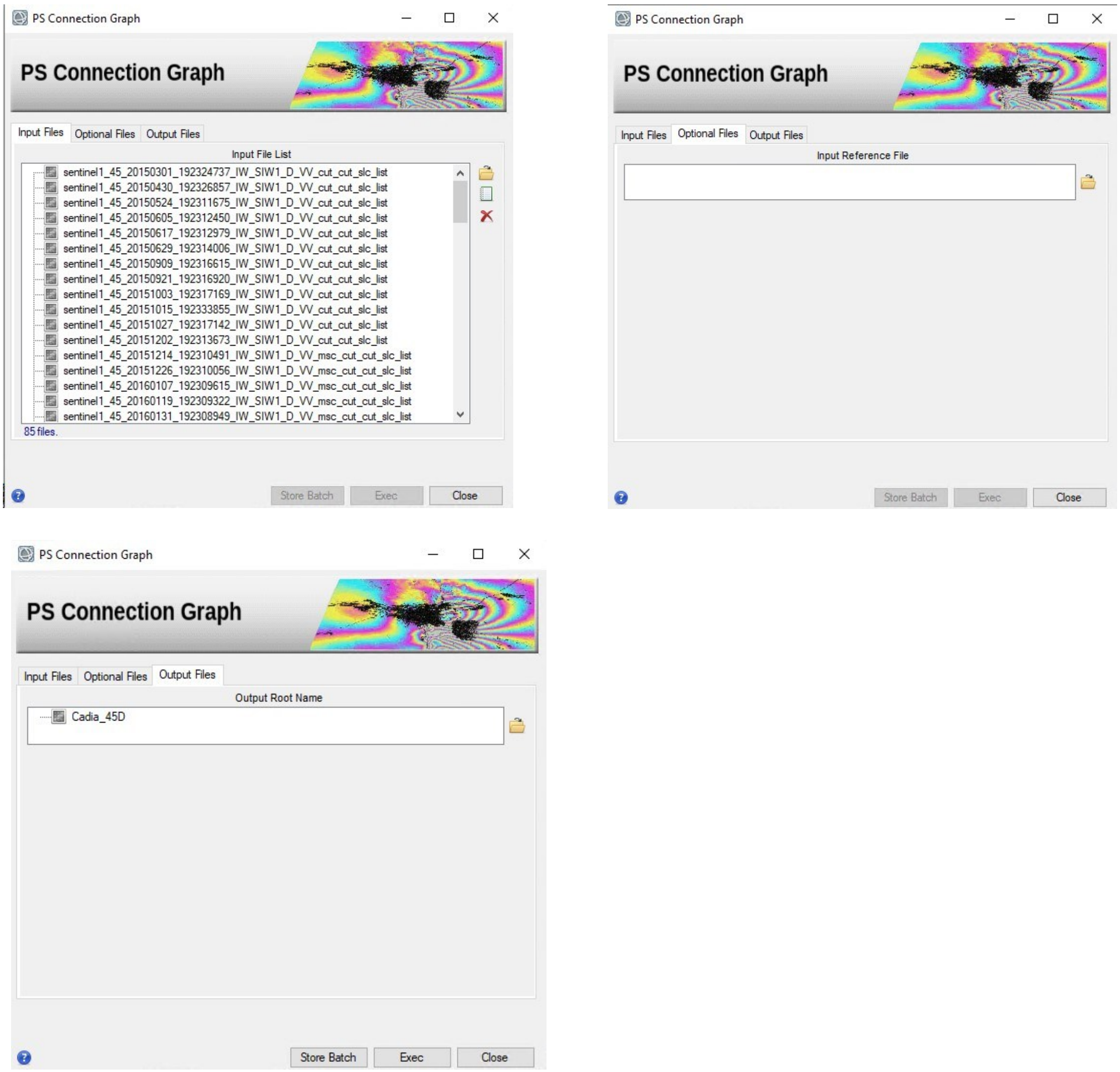


Figure 5 Connection Graph panels.

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

- **Time-Position plot**, which provides, for each Slave acquisition, the satellite normal distance from the Master in meters (y axis) and the input acquisition dates (x axis);
- **Time-Baseline plot**, which provides the satellite normal distance in meters (y axis) and the input acquisition dates (x axis).

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: Master acquisition.

TIPS

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

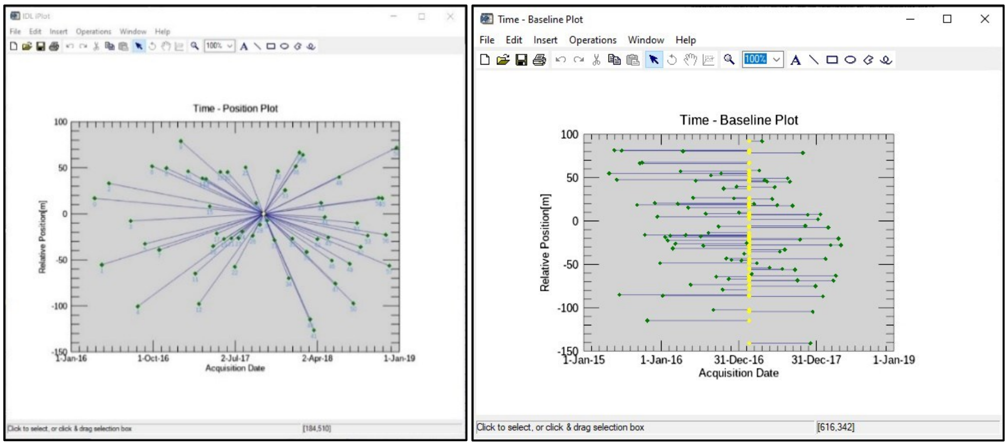


Figure 6 Plots generated by the Connection Graph Generation tool.

Output

The multilooked Master image (suffix, "_pwr") is automatically displayed in ENVI as well (Figure 7).The multilooked factor is automatically computed based on the grid size specified for the sensor once the Preferences was set.

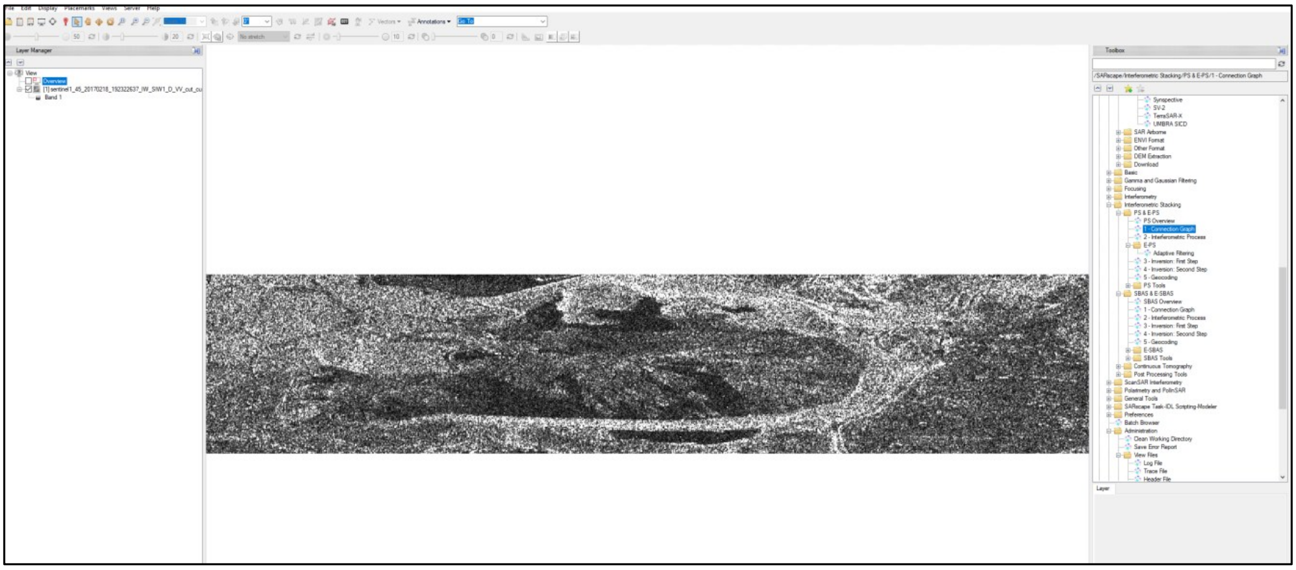


Figure 7 Mooltilooked Master image.

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

The auxiliary file is the main file that guide users in the E-PS processing, all the mandatory PS processing steps are based on the auxiliary file.

The Connection graph folder includes:

- Multilooked Master intensity image (_pwr) and associated header files (.sml, .hdr);
- CG_report, which summarizes the pairs characteristics.

- Report file (Reference_selection.txt), which shows the input selection parameters such as selected master, baseline and theorical precision values, and thresholds, etc;
- **plot** folder, which is used to store the files (CG_baseline.txt and CG_position.txt) used for the visualization of the graphs and interfacing with ENVI.

TIP

This tool performs the E-PS processing in a defined area of interest. If users want to perform a different dataset, they must consider that a full frame processing is fully discourage due to the processing time. To appreciate the influence of the parameters, a sampled dataset is strongly recommended.

Interferometric Process

The Interferometric Process step includes the Coregistration and the Interferogram generation processes

As stated before, the E-PS interferometric process performs an overlooking in order to generate interferometric results. However, these data cannot be visually interpreted because of their geometry.

The E-PS Interferometric Process is performed running the /SARscape/Interferometric Stacking/PS & E-PS/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.

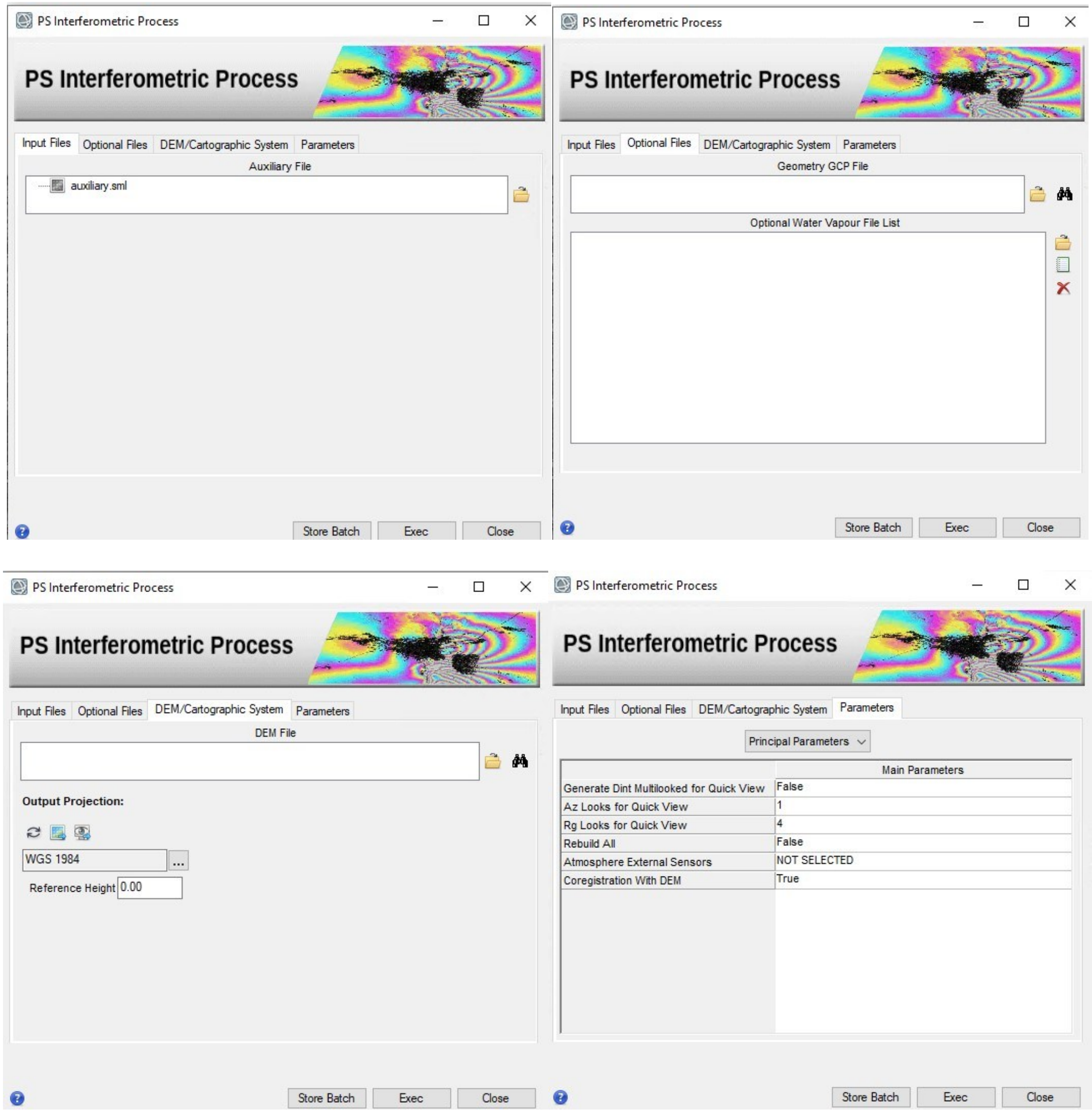


Figure 8 Interferometric Process panels.

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.

TIPS

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.

Adaptive Filtering

Adaptive *Filtering* is mandatory to compute an *E-PS* processing. A standard PS processing is performed in case this step is skipped and the user runs the *First Inversion* after the *Interferometry Process* step.

The purpose of this functionality is to enhance the standard Persistent Scatterer (PS) analysis in rural areas by implementing adaptive filtering on the interferometric phase.

To achieve this, two main steps are required. Firstly, the identification of statistically similar pixel ensembles must be conducted. This involves utilizing the Kolmogorov-Smirnov (KS) and Anderson-Darling (AD) tests based on the amplitude of a co-registered and calibrated stack of SAR data.

Secondly, for all DS identified through the statistical tests, the covariance matrix is estimated by leveraging the ensemble of similar pixels. The SLC phases corresponding to DS are optimally weighted using either the maximum likelihood estimator (MLE) under the assumption of Gaussianity, or by exploiting the largest principal component of the covariance matrix. DS exhibiting a coherence higher than a specified threshold are jointly processed with PS for the final estimation of the displacement time series.

Input files

Insert the auxiliary.sml file.

Parameters

Leave the default parameters except for the Batch size one:

- *Shp Map Method*
  This corresponds to Identification of statistically homogeneous areas (Distributed Scatterers). Two statistical tests are available:
  • Kolmogorov-Smirnov (KS)
  • Anderson Darling (AD)
- *Win Az Size (m)*
  This corresponds to the size of window azimuth size used by the adaptive filter.
- *Win Rg Size (m)*
  This corresponds to the size of window range size used by the adaptive filter.
- *Adaptive Filtering Method*
  This corresponds to Adaptive Spatial Phase Multilooking via Covariance Matrix to filter the DSs. Two filtering methods are available:
  • Maximum Likelihood Estimation (MLE)
  • Principal Component Analysis (PCA)
- *DS threshold*
  These correspond to the threshold used to discriminate PS and DS pixels, based on the statistically homogeneous pixel map. This is retrieved through the statistical test listed in the Shp Map Method filed. The filtering is not applied to those pixels with values lower than this threshold.
- *Delete orig dint files*
  By setting this flag the original dint files, generated during the interferometry step, are deleted.
- *Activate Filtering batch Mode*
  By setting this flag the Adaptive Filtering process is executed in batch mode.
- *Batch size (acq number)*
  This refers to the number of acquisitions to process in batch mode. Set it at 20. It means that a ''batch group'' is made of 20 images.

TIP

The batch process allows for optimizing the processing performance of the adaptive filtering step. It is therefore suggested to enable it when dealing with large datasets. It is important to note that while batch mode improves processing performance, the filtering quality may be slightly affected. For this reason, the batch size needs to be large enough; we suggest no fewer than 10, otherwise, the filtering applied will be based on an inadequate statistical sample.

Rebuild All
By setting this flag the whole Adaptive Filtering 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.

Output

Two sub-folders are created below the path: *ProjectName*_PS_processing\work\work_interferogram_stacking; the names of the two folders are **Filtered** and **Map.**

Filtered:
Directory containing the following products:

- **_rsp_slc**, corresponding to the filtered and coregistered SLC data.
- **cc_ds**, corresponding to the multitemporal coherence of the DS pixels.
- **cc_ds_avg**, corresponding to the average multitemporal coherence. it is generated only in case the batch mode has been enable.

Map:
Directory containing the following product:

•**KS/AD_shp_neighbors**, corresponding to the number of statistically homogeneous pixels. Each value ranges between 1 and the maximum value of the window (rg x az size) converted into pixels.

The folder **work_interferogram_stacking** contains also the *_fil_DS_dint* files which correspond to the filtered interferograms.

Figure 9 is a zoom on the slant-range *dint* file that show the comparison before and after the application of the adaptive filter. Homogeneous areas appear in the filtered _dint image. Inside these new homogeneous areas, there are still single pixels that have not been filtered since they are classified as PS points. This behavior is intrinsic to the adaptive filtering working principle, which filters DS points and keeps the original resolution of the PS ones.

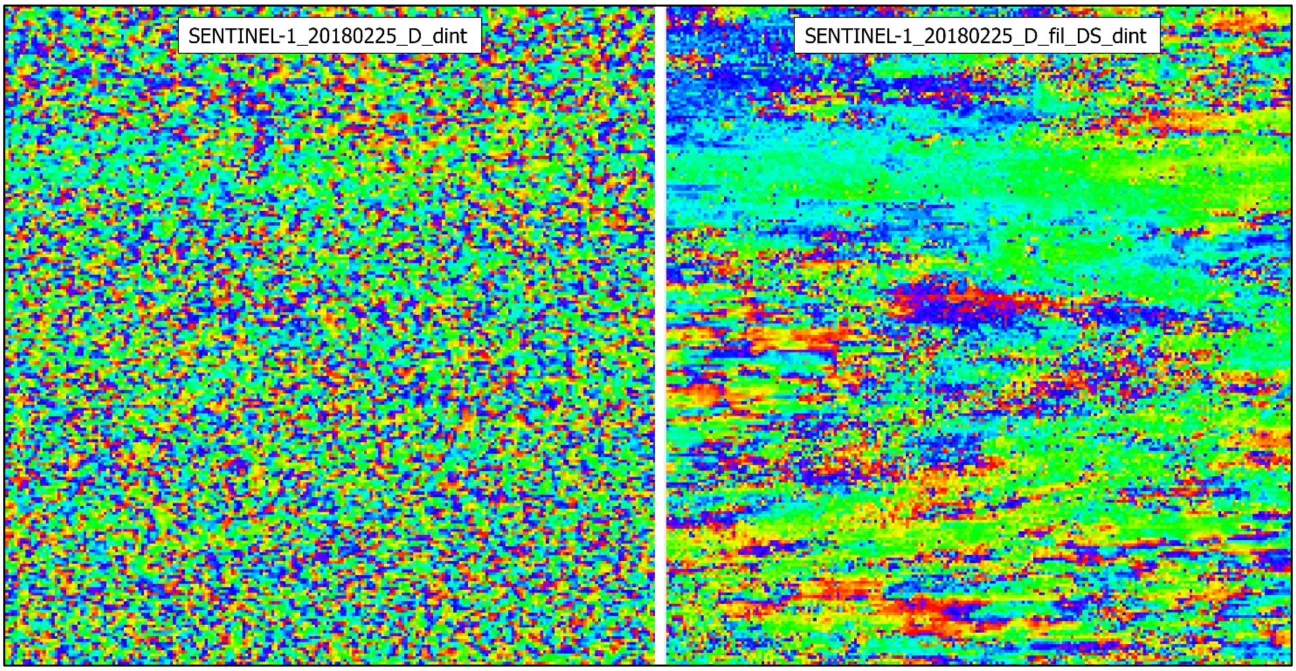


Figure 9 Comparison between the flattened interferogram before and after the application of the adaptive filter.

Inversion: First Step

The **displacement velocity** and **residual height** are derived from the first model inversion without removing any phase component due to the atmosphere. This step is mandatory.

Input files

Insert the auxiliary.sml file.

Parameters

Leave the default parameters.

- *Displacement Sampling (mm/year)*
  Which corresponds to the sampling frequency (in mm/sec) which is used to estimate the displacement velocity.
- *Min Displacement Velocity (mm/year)*
  Which corresponds to the value expected (in mm/year) as the minimum displacement velocity.
- *Max Displacement Velocity (mm/year)*
  Which corresponds to the value expected (in mm/year) as the maximum displacement velocity.
- *Residual Height Sampling (m)*
  Which corresponds to the sampling frequency (in meters) which is used to estimate the residual height.
- *Min Residual Height (m)*
  Which corresponds to the minimum (negative value) residual height, with respect to the reference Digital Elevation Model.
- *Max Residual Height (m)*
  Which corresponds to the maximum (positive value) residual height, with respect to the reference Digital Elevation Model.

- *SubArea For Single Reference Point (sqkm)*
  Which refers to the maximum size for one 'Reference Point'.
- *SubArea Overlap (%)*
  Which refers to the overlap between the sub areas.
- *Number of Candidates*
  For each subarea one or more pixels is/are considered as candidates (Reference Points). The analytic method to define the candidates is based on the Amplitude Dispersion Index. They are automatically analyzed for the calculation of the phase offset and just one will be selected as reference point.
- *Rebuild All*
  By setting this flag the whole PS Inversion process is started from scratch.

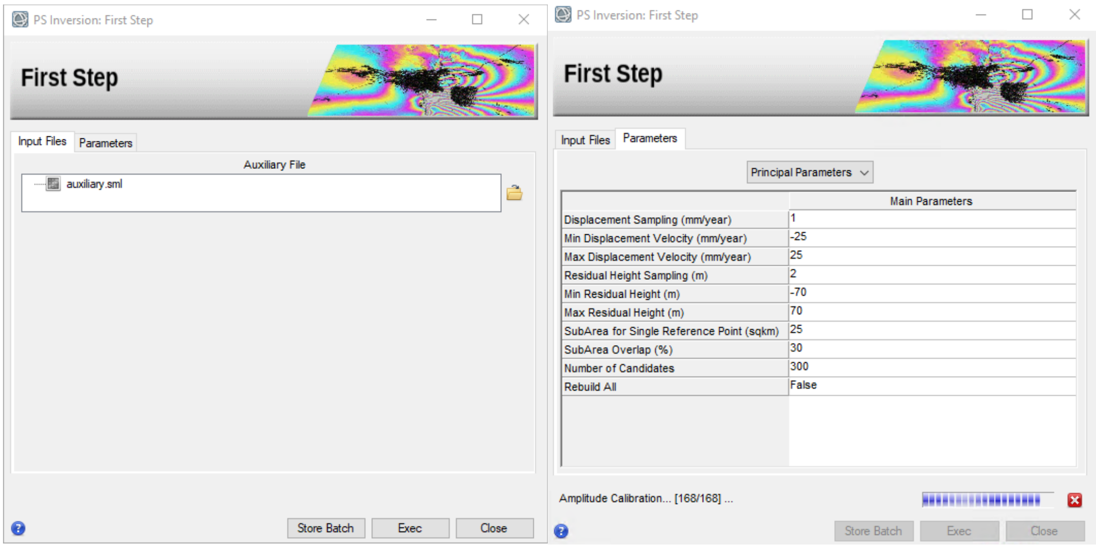


Figure 10 First Inversion panels

Output

The **first_inversion** folder includes:

- Height_first: corresponding to the correction (in meters) with respect to the input Digital Elevation Model.
- Velocity_first: corresponding to the preliminary estimation of mean displacement velocity (in mm/year).
- cc_first: corresponding to multitemporal coherence.
- Cohe_Sub_Areas_meta: meta file of the coherence, for area larger than 25 km^2.
- H_Sub_Areas_meta: meta file of the heights, for area larger than 25 km^2.
- Vel_Sub_Areas_meta: meta file of the velocities., for area larger than 25 km^2.
- Ref_GCP.shp: which refers to the GCPs selected on the image, in slant range geometry.
- SubAreas.shp: which refers to the sub-areas (slant range geometry) computed according to the atmospheric parameters, (refer to the Preferences>Persistent Scatterers>Area for Single Reference Point and 'Area Overlap for SubAreas).

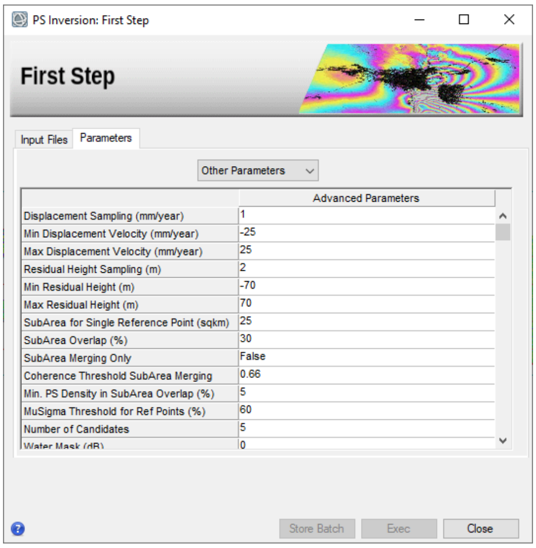


Figure 11 Other Parameters panel.

To check the results, the "Velocity_first" and "Height_first" has to be loaded in ENVI, together with the SubAreas.shp.

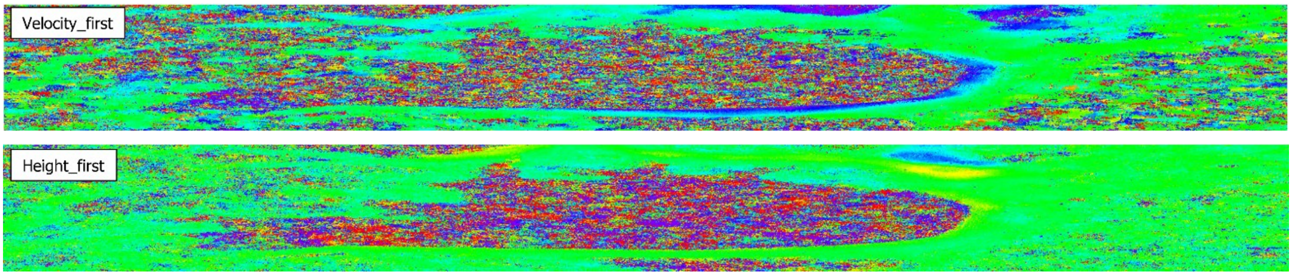


Figure 12 Velocity_first and Height_first.

TIP

Users can edit the size of the field *SubArea For Single Reference Point (sqkm)* to reduce the effects of atmospheric residuals. For example, in such cases where isolated atmospheric bubbles are present, a lower sub areas extension helps to better remove these kind of effects. The current AOI is smaller than 25 km^2 and therefore one single sub-area is created.

Inversion: Second Step

The second inversion uses the output of the first inversion to **estimate the atmospheric phase** components.

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.

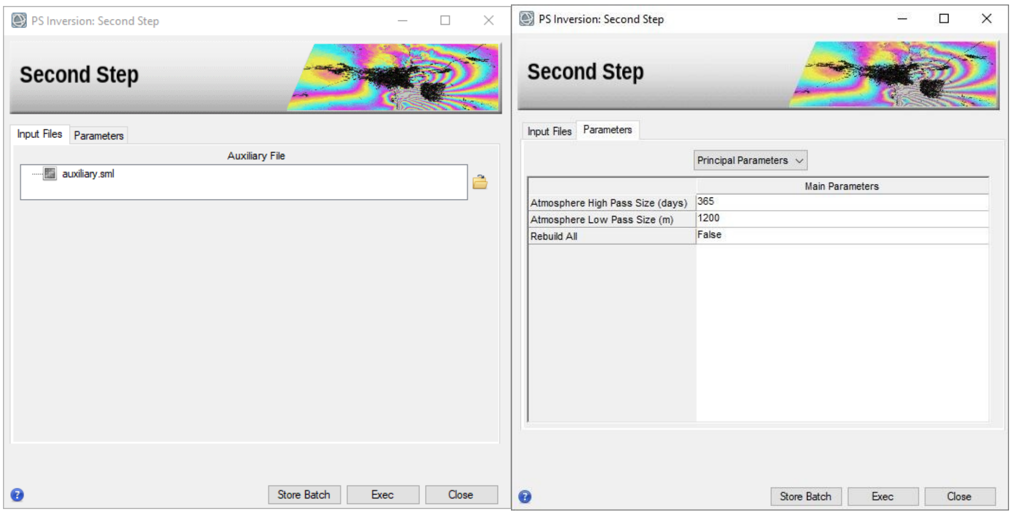


Figure 13 Second Step panels for input and parameters.

Output

The **second_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,** corresponding to multitemporal coherence. It shows how much the displacement trend fits with the selected model.

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

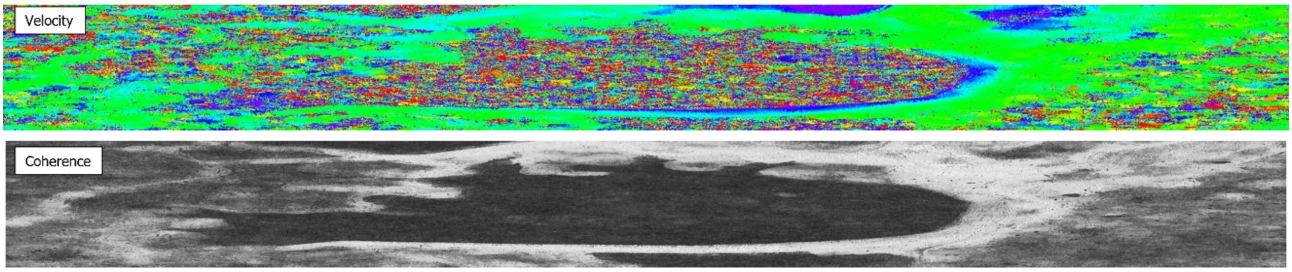


Figure 14 Velocity and coherence layers generated during the Second Inversion step. The dark areas visible in the coherence layer correspond to low coherence areas, while the brighter ones correspond to areas with higher values of coherence.

Geocoding

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

Input files

Insert the auxiliary.sml file.

Refinement GCP File

Leave the default parameters.

> TIP
>
> 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 Srtm-1_V3_dem provided in the input dataset.

Parameters

Leave the default parameters.

- *Product Temporal Coherence Threshold*
  Pixels with temporal coherence values smaller than this threshold will be set to dummy (NaN) as Persistent Scatterers in the final products

- *Generate KML*
  By setting this flag the Google Earth .kml of the resulting PS 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 Shape*
  By setting this flag the slant range products are geocoded onto the Digital Elevation Model cartographic reference system and the ultimate PS products are generated in vector format. By default, this option is flagged. The Geocoded product can be projected along both the maximum slope direction (_SD), on the vertical plane (_VD) or a custom direction. The proper flag below must be activated.

- *Make Geocoded Raster*
  By setting this flag the slant range products are geocoded onto the Digital Elevation Model cartographic reference system and the ultimate PS products are generated in raster format. The Geocoded product can be projected along both the maximum slope direction (_SD), on the vertical plane (_VD) or a custom direction. The proper flag below must be activated.

- *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 second inversion folder.

- *Rebuild All*
  By setting this flag the whole geocoding process starts 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.

- *Refinement Stacking*
  The user can choose between the following options:
    - Stack Velocity Disp Refinement.
    - Stack Residual Height Refinement.
    - Stack All Products Refinement: The refinement process will be applied to the Velocity, to the Height or to both layers according to the chosen option. The refinement GCP file must be uploaded.

- *Refinement Radius (m)*
  Maximum buffer radius for the association of Ground Control Point with respect to the slant range unwrapped phase closer valid pixel.

- *Refinement Displacement Poly Degree*
  Degree of the polynomial used to estimate the displacement ramp, which will be removed from the input displacements date by date 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 displacement ramp in range and azimuth direction plus a constant displacement offset will be corrected. In case only the displacement offset correction is needed, the polynomial degree will be set to 1.

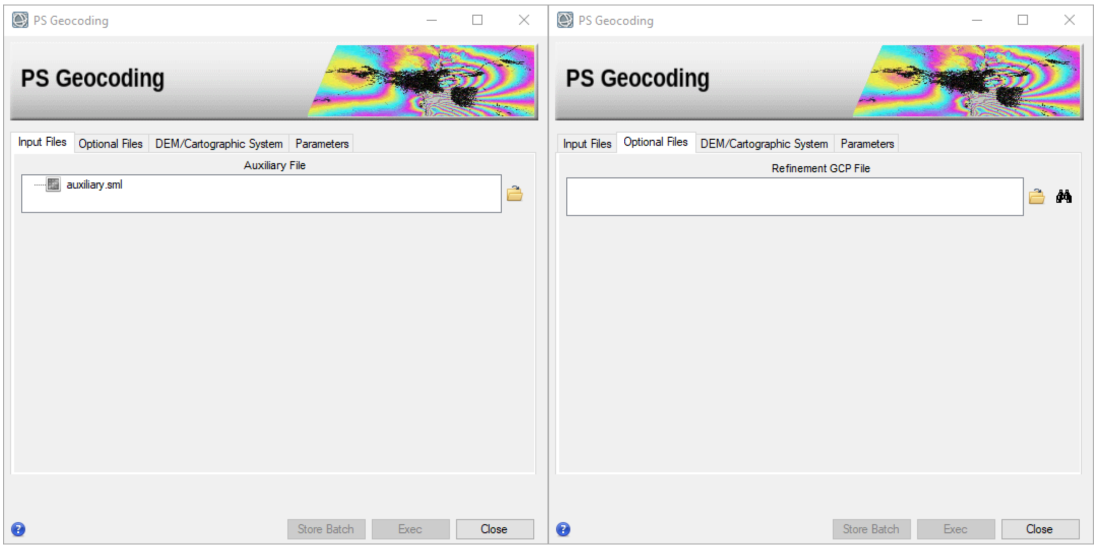
- *Vertical Displacement*
  By setting this flag the displacements and velocity products are projected in the vertical direction.

- *Slope Displacement*
  By setting this flag the displacements and velocity products are projected along the maximum slope.

- *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 in the specified direction is generated among the output products.

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

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



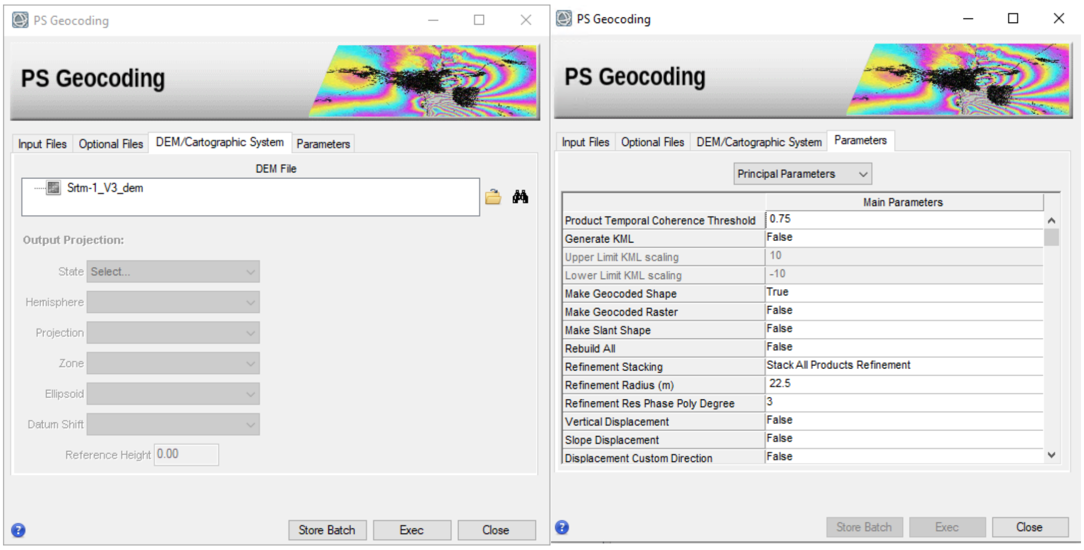


Figure 15 Geocoding panels.

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_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 in mm/y
- -coherence: multi-temporal coherence, it is a quality index for the best fitting of interferometric phase date by date
- -MuSigma: it is the amplitude dispersion index, it is the mean/standard deviation ratio, where mean corresponds to a temporal mean
- shp nbr: it corresponds the number of statistical homogeneous pixels
- Scatterer: it defines if a point is a PS or a DS
- -Hprecision: it corresponds to the estimate in meters of the height measurement average precision. It is computed considering the acquisition spatial baseline and the multitemporal coherence
- -Vprecision: it corresponds to the estimate of the velocity measurement average precision in millimeter/year. It is computed considering the acquisition temporal baseline and the multitemporal coherence
- -range: pixel coordinate
- -azimuth: pixel coordinate
- SubArea: SubArea Id
- -lon/ lat: geographic coordinates
- -xpos/ypos cartographic coordinates based on the DEM reference system
- -zpos: elevation in m based on the DEM ellipsoid model
- -Z: Elevation based on the geoid component
- -ALOS: Line of Sight Incidence angle on Azimuth direction
- -ILOS: Line of Sight Incidence angle on vertical direction

- -Hcorrection: it corresponds to the correction (in meters) with respect to the input Digital Elevation Model.
    - -D_date: displacement acquisition date in meters.
- EPS_disp_geo_XX_meta: This meta file is created if "Make Geocoded Raster" is selected. It contains the following files called *EPS_XX_cc_geo, *EPS_XX_vel_geo, *EPS_XX_height_geo (for coherence, velocity and height residuals), EPS_ALOS, EPS_ILOS, and data_XX_disp_geo (date by date).* is the output root name chosen in the connection graph step. while XX is the decimal part of "Product Coherence Threshold" (0.XX).
- 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 step 1.
- SubAreas_geo: shape file corresponding to the sub areas estimated according to the "Area For Single Reference Point" parameter.

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 Shape 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). In this tutorial, only vector results are taken into account.

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 must be set in the panel, the Color Apply button allows displaying the data range on the PS shapefile. Once the desired PS/DS is selected, click on "*Plot Time Series*" 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 by 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.

TIPS

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

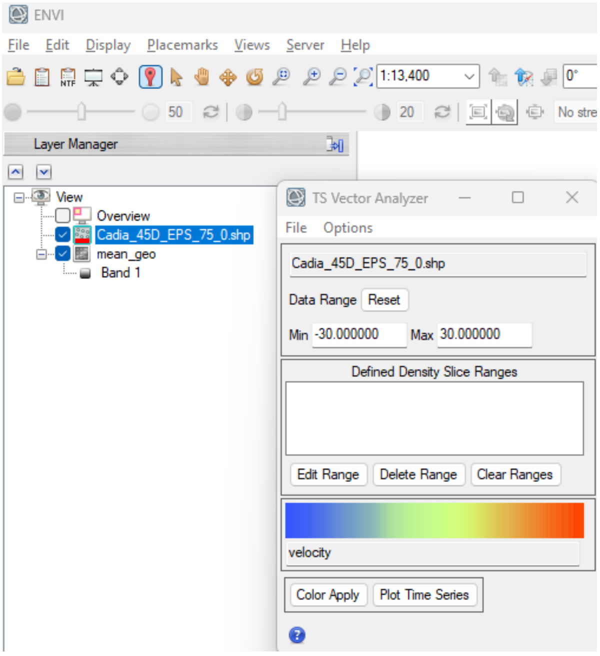


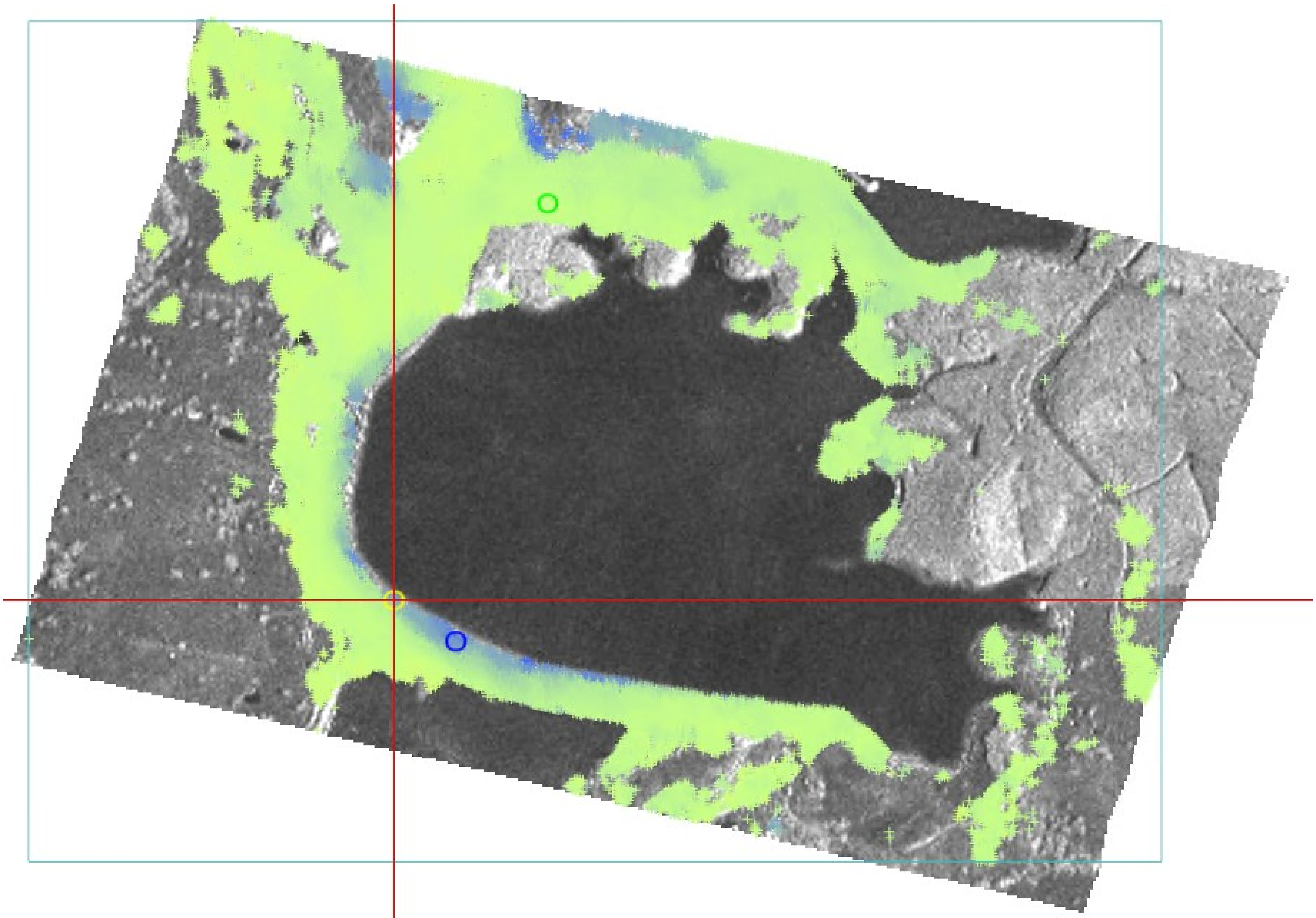
Figure 16 Time Series Panel.

Results

The results of the E-PS processing in the Cadia area can be seen in Figure 17. 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 red and blue place marks of the selected points show the location of the corresponding time series.

The green point correspond to a stable pixel, the blue point shows a cumulative displacement of around 70 millimeters and the yellow one is in correspondence of the collapsed area and the time series shows a "jump" likely due to an strong acceleration that occurred in that area of the TSF time series. Note that the PS technique can mostly estimate linear displacement trends, therefore such acceleration, if strong, could not be resolved. The SBAS/E-SBAS technique could be instead considered to monitor such time series patterns since the temporal unwrapping process is performed.



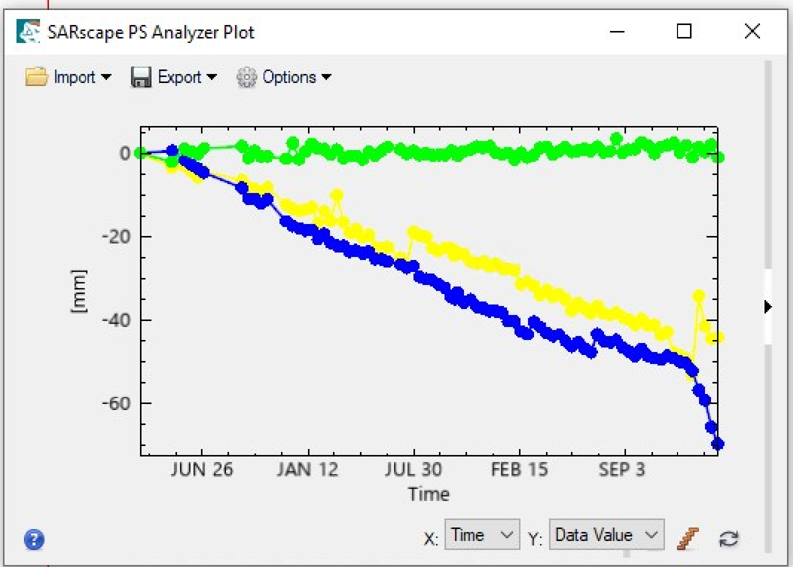


Figure 17 E-PS Velocity Map and Time series plot of the two selected points.

It is worth mentioning that, due to limitation on the shapefile format, it cannot exceed 2 GB, thus allowing approximately 70-million-point features at most. For this reason, PSs points are split into different shapefiles.

In this case the shape file is made of approximately 39,000 points therefore only one shape file has been created.

A comparison between the PS and the E-PS results obtained with the same data stack is shown in Figure 18. The comparison highlights the improved coverage obtained with the E-PS technique, especially over vegetated areas. The shapefile obtained with the PS technique includes around 8,700 points, which is about four times fewer than those included in the shapefile generated using the E-PS technique.

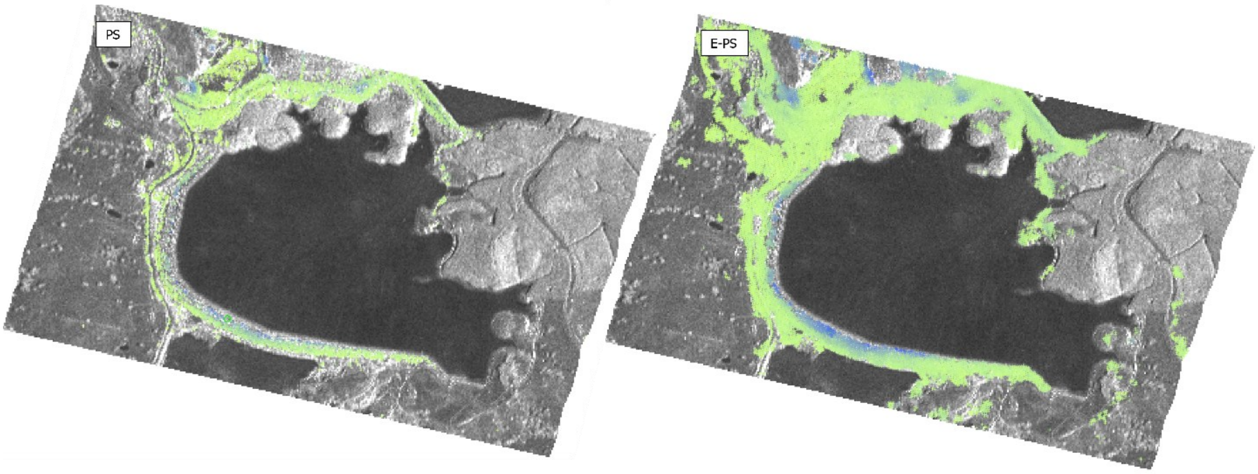


Figure 18 PS - EPS vector velocity map comparison.

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. PS Compute Specific Sub-Area

During the first PS inversion, in some circumstances, some Sub-Areas can show wrong velocity and height values if these are computed using a wrong reference point (automatically chosen).

This tool allows us to re-compute the velocity and height values for these sub areas where the results are not satisfactory (e.g.: discontinuities in velocity or height values or very low coherence over urban areas) by letting the user have the possibility to manually choose the reference point.

Note: The screenshots visible in this paragraph are relevant to another dataset consisting of multiple sub-areas.

This tool should be used after the PS Inversion: First Step if the value of velocity and height of one or more Sub-Areas are not satisfactory.

These values can be checked by opening the files "cc_first", "Height_first" and "Velocity_first". The reference points used are stored in the "Ref_GCP.shp" file and the Sub-Areas in the "SubAreas.shp" file. All these files are in the "first_inversion" directory, inside the PS_processing folder.

Each Sub-Area is separately computed with its own Ref Point; to find out the ID number of a given Sub-Area, please move the "SubAreas.shp" file at the top of the Layer Manager in ENVI, right click on the "SubAreas.shp" in the Layer Manager and then "View/Edit Attributes". Now, when a Sub-Area is clicked, the Attribute Viewer will highlight the ID Polygon.

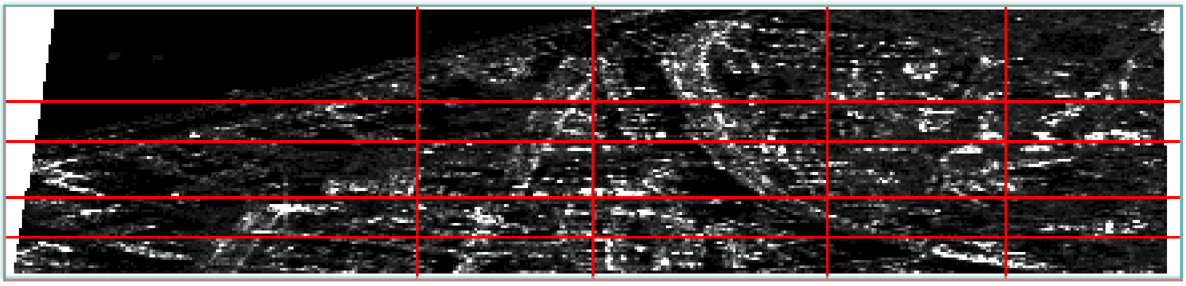


Figure 19 Visualization of the Sub Areas

Velocity jumps can occur after the first inversion step because of GCPs automatically selected by the algorithm for one or more sub-areas.

As shown in Figure 21, a large blue area appear in the geocoded result, the same area is highlighted in orangish in the *velocity_first* layer, Figure 20 (orange area with opposite sign, for the ENVI color bar).

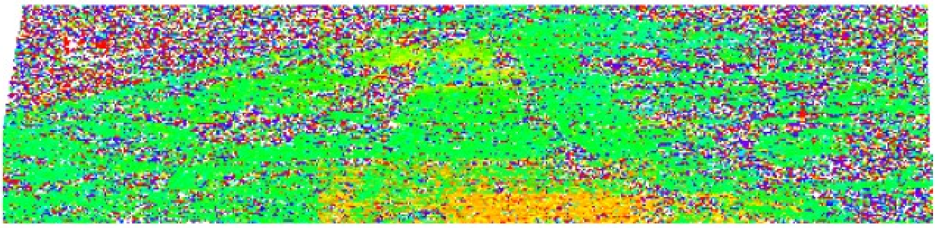


Figure 20 Velocity_first layer in slant-range coordinates.

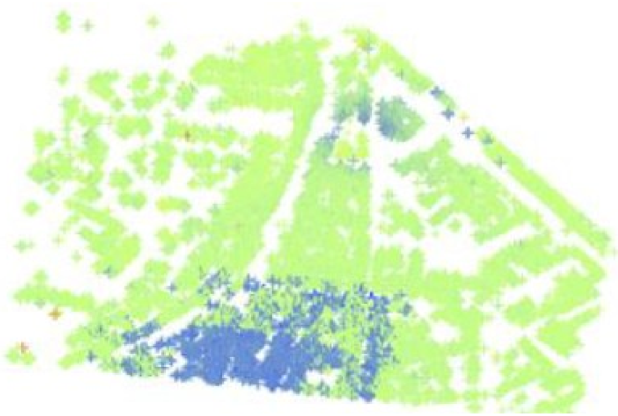


Figure 21 PS output layer

To remove this unexpected phase jump, perform the following steps:

- After loading the SubAreas.shp in ENVI it is possible to identify the ID/IDs of the specific sub-area/sub-areas showing velocity jumps. Please note the ID of the Sub-Areas that needs to be "corrected" and insert it in the *Id Sub-Area* field.

- After that, it is necessary to choose the new GCP point, therefore take note of the coordinates in slant-range of the desired GCP and insert them in the fields *Ref Point Rg* Value and Ref *Point Az Value.* The selected GCP should be placed on pixel with a good mu-sigma value. The GCP can be placed anywhere in the image, of course the closer the GCP to the to the sub-area, the better.

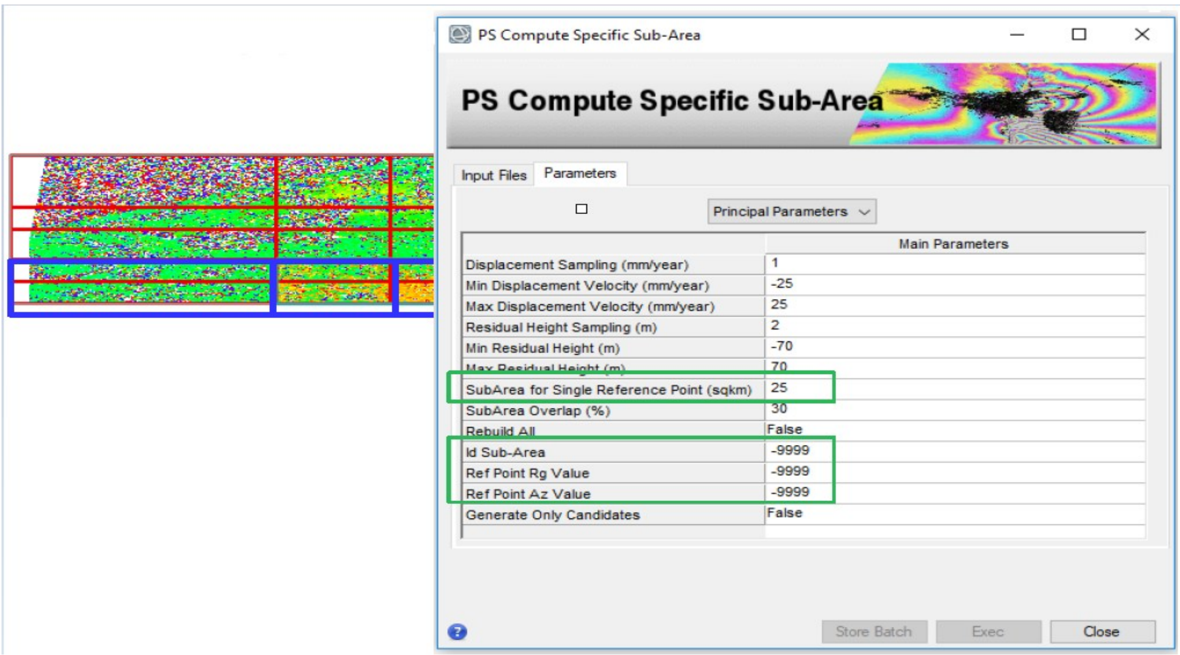


Figure 22 PS Compute Specific Sub-Area panel

The "Generate Only Candidates" should remain set to False. If this flag is set to true it will create a document showing the best 10 candidate reference points (please refer to the technical notes on the relevant Help page). To perform the processing please set this flag to false.

- Click on the *Exec* to start the sub area edit process.

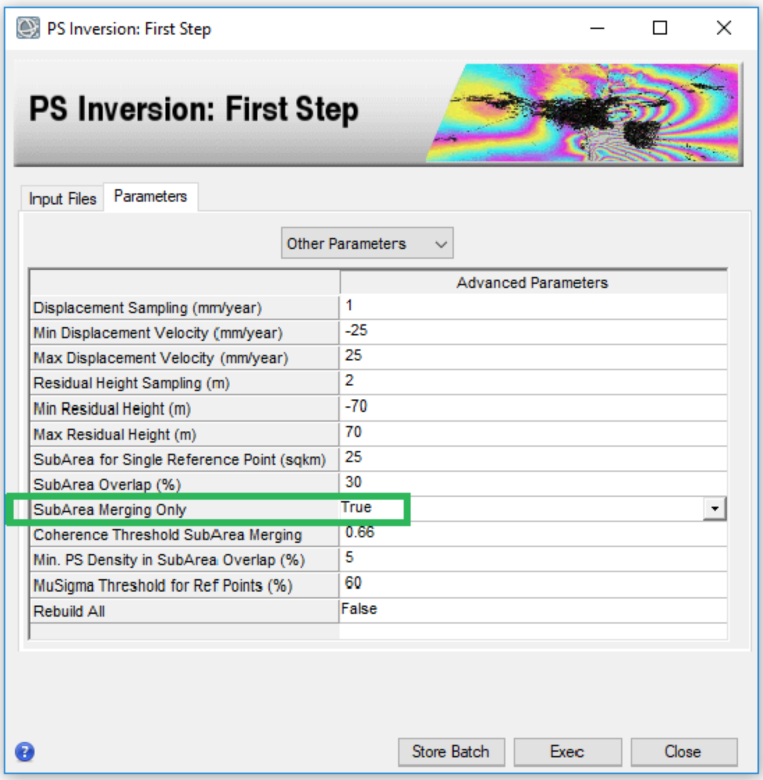


Figure 23 SubArea merging Only parameter set to true

- Open the PS First Inversion Step and open the *Other Parameters* panel, then set to True the *SubArea Merging Only field,* this is necessary to prevent the whole First Inversion step to be computed.
- Click on the *Exec* button.
- Once the First Inversion step is completed run the Second Inversion and Geocoding steps from scratch.
- Figure 24 and Figure 25 shows the improvement of the sub area edit process.

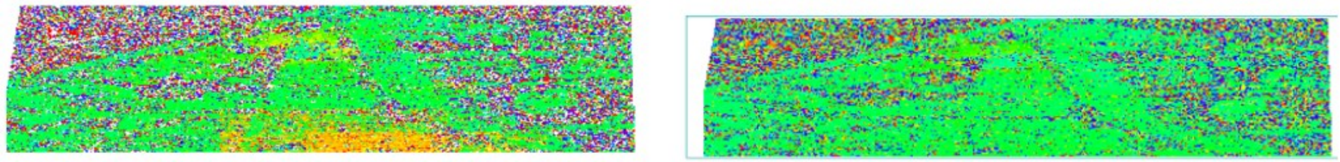


Figure 24 Velocity first layer, before (left) and after (right) the sub area edit process.

Figure 25 PS output layer before (left) and after (right) the sub area edit process.

Annex 2. GCP selection

The reference points, for each sub-area, are automatically defined during the first inversion based on 300-pixel candidates (default number). The algorithm iteratively uses all the 300 candidates as reference points to calculate the multi-temporal coherence on all the pixels that compose the image; the candidate that provides the best result in terms of multi-temporal coherence will be used as a reference point.

During the First Inversion the candidates are selected automatically, it is not possible for the user to manually select a list; from our experience we saw that it is not worth leaving the possibility to select the candidates to users, since most of the time you get unreliable results. Anyway, now it is possible to change the reference point of the single Sub areas with the dedicated tool: PS Compute Specific Sub-Area (Interferometric Stacking/Stacking Tools/PS Compute Specific Sub-Area, Annex 2. GCP selection).

During the Geocoding process, instead, the user can insert one or more GCPs (under the Optional Files tab) that will be used as reference points, with 0 velocity, to calibrate the rest of the pixels. In case the user does not manually insert the GCP, the software will choose the best (according to the MuSigma value) one among the GCPs created for each sub-area. The list of GCP is stored in the Ref_GCP.shp file.