DEM generation with Sentinel-1
Workflow and challenges

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Interferometry Tutorial

The goal of this tutorial is to provide novice and experienced remote sensing users with step-by-step instructions on interferometric processing with Sentinel-1 Interferometric Wide Swath products for DEM generation.

Background

What is Interferometry?
Interferometric synthetic aperture radar (InSAR) exploits the phase difference between two complex radar SAR observations taken from slightly different sensor positions and extracts information about the earth’s surface.

A SAR signal contains amplitude and phase information. The amplitude is the strength of the radar response and the phase is the fraction of one complete sine wave cycle (a single SAR wavelength). The phase of the SAR image is determined primarily by the distance between the satellite antenna and the ground targets.

By combining the phase of these two images after coregistration, an interferogram can be generated whose phase is highly correlated to the terrain topography. However, there are many other contributions to the phase image which potentially decrease the quality of the resulting elevation product, such as atmospheric disturbances, unwrapping errors and decorrelation due to surface changes.

For an introduction to interferometric concepts, please see ESA’s InSAR Principles: Guidelines for SAR Interferometry Processing and Interpretation (ESA TM-19).

Sentinel-1 Interferometric Wide Swath Products

The Interferometric Wide (IW) swath mode is the main acquisition mode over land for Sentinel-1. It acquires data with a 250 km swath at 5 m by 20 m spatial resolution (single look). IW mode captures three sub-swaths using Terrain Observation with Progressive Scans SAR (TOPSAR). With the TOPSAR technique, in addition to steering the beam in range as in ScanSAR, the beam is also electronically steered from backward to forward in the azimuth direction for each burst, avoiding scalloping and resulting in homogeneous image quality throughout the swath.

TOPSAR mode replaces the conventional ScanSAR mode, achieving the same coverage and resolution as ScanSAR, but with a nearly uniform SNR (Signal-to-Noise Ratio) and DTAR (Distributed Target Ambiguity Ratio).

IW SLC products consist of three sub-swaths (Figure 1, red labels) image per polarization channel, for a total of three (single polarizations) or six (dual polarization) images in an IW product. Each sub-swath image consists of a series of bursts (Figure 1, white labels), where each burst has been processed as a separate SLC image. The individually focused complex burst images are included, in azimuth-time order, into a single sub-swath image with black-fill demarcation in between, similar to ENVISAT ASAR Wide ScanSAR SLC products.

More information on Sentinel-1 IW products is provided here: https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/acquisition-modes/interferometric-wide-swath.

The data used in this tutorial lies in eastern Turkey and includes the city of Erzincan and its surrounding landscapes. Figure 2 shows the extent of the Sentinel-1 data (red) and of the subset used in this tutorial (blue).
Figure 1: Sub-swaths (red) and bursts (white) of S1 IW products

Figure 2: Extent and location of the data
Preparation

Selection of suitable images
A crucial step for a successful DEM generation is the selection of an image pair with suitable properties. Among others, favorable conditions include:

- **Short temporal baseline**: The time between the first and the second image should be kept as short as possible to reduce the risk of temporal decorrelation of the phase. Whenever surfaces change between the first and the second acquisition, the signal will be out-of-phase and no longer exploitable (Figure 3, right). This happens over vegetation and water areas, but also under changing moisture conditions, moving objects etc. Especially C-band radar (Sentinel-1) is prone to temporal decorrelation because of the comparable short wavelength. Smaller areas of decorrelations are tolerable but large parts of the image should produce an interferogram with clearly visible fringes and high coherence (see chapter “Interferogram Formation and Coherence Estimation”). Accordingly, generating DEMs from Sentinel-1 over vegetation areas will produce bad results. If you have strong seasonality, try to find image pairs at times of minimum vegetation cover.

- **Suitable perpendicular baseline**: The distance between the satellites’ positions at the time of image acquisition should be between 150 and 300 meters (ESA TM-19B, chapter 1.4). This grants an angle between both acquisitions which allows to retrieve topographic variations from parallax-like effects: targets of different heights are displaced relative to each other in the two images based on their altitude (Rosen et al. 2000). If the perpendicular is too small, these topographic effects on the differential phase are not pronounced enough. With too large baselines, the coherent phase is increasingly different, also leading to decorrelation. The Sentinel-1 mission was mainly designed for the retrieval of deformations (DInSAR) and not for DEM generation (Geudtner et al. 2016). Most of the baselines between two consecutive images are below 30 meters. **Image pairs with short temporal baselines and large perpendicular baselines can be hard to find.**

A helpful tool to identify the baseline of two images and to find suitable image pairs is provided by the Alaska Satellite Facility: [ASF Baseline tool](https://www.asf.alaska.edu/)

- **Suitable atmospheric conditions**: Water vapor in the atmosphere causes phase delays and potentially decreases the quality of the measurement. It is therefore advisable to select images acquired during dry periods and to make sure that no rainfall occurred during both image acquisitions.

![Image geometry and phase decorrelation](https://www.asf.alaska.edu/)
Download the Data

The data used in this tutorial can be downloaded from the Copernicus Open Access Hub at: https://scihub.copernicus.eu/dhus (login required, registration is free)

Search for the two product IDs and download them:
S1B_IW_SLC__1SDV_20190702T032447_20190702T032514_016949_01FE47_69C5
S1A_IW_SLC__1SDV_20190708T032532_20190708T032559_028020_032A14_33CA

As some of the required steps are computationally intensive, it is good to store the data at a location which offers good reading and writing speed. If your computer has an internal SSD, processing should be done there to ensure best performance. Network drives or external storage devices are not recommended. Also, paths which include special characters should be avoided. In this tutorial, the data is stored under C:\Temp\S1_InSAR_DEM.

Install snaphu

This tutorial can entirely be done within SNAP. Yet, as an external software package, snaphu (statistical-cost network-flow algorithm for phase unwrapping) has to be installed separately. For more information on this tool, please visit https://web.stanford.edu/group/radar/softwareandlinks/sw/snaphu/.

To install the plugin in SNAP, go to Plugins (under the Tools menu, Figure 4) and search for “SNAPHU Unwrapping” in the Available Plugins tab. Select it and click Install.

You will be asked to proceed with “Next” and restart SNAP (Figure 5). This creates a menu entry for snaphu unwrapping in the Interferometry menu.
After you have restarted SNAP, you need to install the snaphu bundles as well. Go to Manage External Tools in the Tools menu. Select “Snaphu-unwrapping” and click Edit the selected operator to open the configuration (Figure 6). Select a suitable Target Folder (here C:\GIS) where snaphu will be installed and proceed with Download and Install Now. You will then get a confirmation “Bundle was installed in location C:\GIS\snaphu-v1.4.2_win64” (this may differ according to version, path and operating system).

Figure 5: Installation of the snaphu plugin

Figure 6: Installation of the snaphu bundles
**Open the Products**

Use the ![Open Product] button in the top toolbar and browse for the location of the downloaded data. Select the two zip files and press Open Product.

In the Products View you will see the opened products. Each Sentinel-1 product consists of Metadata, Vector Data, Tie-Point Grids, Quicklooks and Bands (which contains the actual raster data, organized by polarization and sub-swath as demonstrated in Figure 1).

As the data is still compressed in the zip file and each sub-swath covers a large area, it is not advised to open the bands in their current state, because it takes a considerable time until SNAP loads the raster. If you still want to check the data before proceeding double-click on the **Intensity_IW1_VV** band to view the raster data.

Another way to identify the location of your study area within the product (required for the next step), you can use the World View or World Map (to see its full extent on a base map) or open the Quicklook for a preview of the dataset in an RGB color representation.

Note: If you miss any items in your user interface you can activate them in the menu under View and Tool Windows.

The World View or World Map menus are also a good way to check if your image belong to the same relative orbit (required for interferometry) and if they are shifted along-track, as it is the case here. It is not a problem for interferometry but needs to be taken into account in the next step (TOPS Split).

**Coregistration**

To exploit the phase difference of the acquisitions, a stack containing both products must be created first. Coregistration makes use of image statistics to align both products at sub-pixel accuracy. While conventional Stripmap radar products can be coregistered within one step, S1 TOPSAR products require a series of steps, because of their special form of acquisition (Figure 1).

SNAP offers to combine all these steps within the **S-1 TOPS Coregistration with ESD** operator, but this processing chain consumes a lot of memory. In this tutorial, the single steps to correctly coregister the products are performed individually and successively.
**TOPS Split**

*S-1 TOPS Split* is applied to the data to select only those bursts which are required for the analysis. They are marked in blue in Figure 1. Currently, each Sub-Swath is processed separately. Note: If the area of interest covers several Sub-Swaths, they have to be merged with the *S-1 TOPS Merge* operator after the Sub-Swaths were debursted.

To reduce the loaded data to the area of interest, open the *S-1 TOPS Split* operator (under Radar > Sentinel-1 TOPS) and select sub-swath IW2 and VV polarization in the Processing Parameters.

Because the two products are shifted along-track (Figure 7), different bursts have to be selected for each product. Reduce the bursts by dragging the grey triangles towards the middle as defined in the following table:

<table>
<thead>
<tr>
<th>Input product</th>
<th>Subswath</th>
<th>Polarisation</th>
<th>Bursts</th>
<th>Output name</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1B_IW_SLC_1SDV_20190702...</td>
<td>IW2</td>
<td>VV</td>
<td>3 - 5</td>
<td>S1B_20190702_split</td>
</tr>
<tr>
<td>S1A_IW_SLC_1SDV_20190708...</td>
<td>IW2</td>
<td>VV</td>
<td>1 - 3</td>
<td>S1B_20190708_split</td>
</tr>
</tbody>
</table>

Use the preview to check the location of the selected area (Figure 8). Confirm with Run and repeat the step for the second S1 image.

![Figure 8: TOPS Split](image)

**Applying Orbit Information**

Orbit auxiliary data contain information about the position of the satellite during the acquisition of SAR data. They are automatically downloaded for Sentinel-1 products by SNAP and added to its metadata with the *Apply Orbit File* (under the menu point Radar) operator.

The Precise Orbit Determination (POD) service for Sentinel-1 provides restituted orbit files and precise Orbit Ephemerides (POE) orbit files. POE files cover ca. 28 hours and contain orbit state vectors at intervals of 10 seconds intervals. Files are generated one file per day and are delivered within 20 days after data acquisition.
If precise orbits are not yet available for your product, restituted orbits can be selected which may not be as accurate as the Precise orbits but will be better than the predicted orbits available within the product.

Execute the operator for both split products as generated in the previous step (Figure 9).

![Figure 9: Apply Orbit File](image)

**Back Geocoding and Enhanced Spectral Diversity**

The S-1 Back Geocoding operator (under Radar > Coregistration > Sentinel-1 TOPS Coregistration) coregisters the two split products based on the orbit information added in the previous step and information from a digital elevation model (DEM) which is downloaded by SNAP.

Add the products of the two dates (ending with ",_split_Orb") to the file list in the ProductSet-Reader tab and select SRTM 1Sec HGT (AutoDownload) in the Back-Geocoding tab (Figure 10).

Please be aware that SRTM is only available between 60° North and 54° South. If your area lies outside this coverage ([https://www2.jpl.nasa.gov/srtm/coverage.html](https://www2.jpl.nasa.gov/srtm/coverage.html)), you can use one of the other DEMs with AutoDownload option or use an external DEM (just make sure it stored as a GeoTiff and projected in geographic coordinates / WGS84).

![Figure 10: Back Geocoding](image)
To increase the quality of the coregistration you apply the *S-1 Enhanced Spectral Diversity* (ESD) operator (under *Radar > Coregistration > Sentinel-1 TOPS Coregistration*) on the stack generated by the Back Geocoding. It applies range and azimuth shift corrections to the slave image.

Note: This operator is only needed when you select more than one burst. If you only selected one burst in the TOPS Split step, you do not need the ESD operator.

After the coregistration is completed, it is advisable to visually check the quality of the stack. This can be done by an RGB representation of the master and slave product which shows if the images are correctly aligned. Select the master for red and green and the slave for blue (Figure 11).  

![Figure 11: Generation of an RGB image](image)

Zoom in to an area with distinct surfaces, for example the border between land and water. The RGB image should be clear and sharp and not be dominated by one of the images (yellow [red+green] for the master or blue for the slave image). The only exception are changes in landcover or scattering mechanisms which occurred in the time between the first and the second image acquisition (Figure 12).

![Figure 12: Successful (top) vs. failed (bottom) coregistration in an RGB image](image)

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Interferogram Formation and Coherence Estimation

An interferogram is formed by cross multiplying the master image with the complex conjugate of the slave. The amplitude of both images is multiplied while the phase represents the phase difference between the two images.

The interferometric phase of each SAR image pixel would depend only on the difference in the travel paths from each of the two SARs to the considered resolution cell. Accordingly, the computed interferogram contains phase variation \( \phi \) from several contributing factors, most importantly the flat-earth phase \( \phi_{\text{flat}} \) (earth curvature), the topographic phase \( \phi_{\text{DEM}} \) (topographic surface of the earth), atmospheric conditions \( \phi_{\text{atm}} \) (humidity, temperature and pressure change between the two acquisitions), and other noise \( \phi_{\text{noise}} \) (change of the scatterers, different look angle, and volume scattering), and lastly the eventual surface deformation \( \phi_{\text{disp}} \) which occurred between the two acquisitions (Equation 1).

A more detailed explanation is given by Roca et al. (1997), and in the documents compiled by ESA: InSAR Principles: Guidelines for SAR Interferometry Processing and Interpretation (ESA TM-19).

\[
\phi = \phi_{\text{DEM}} + \phi_{\text{flat}} + \phi_{\text{disp}} + \phi_{\text{atm}} + \phi_{\text{noise}}
\]  

Figure 13: Contributors to SAR interferometric phase

Traditional SAR interferometry tries to estimate the contribution from the earth’s surface (\( \phi_{\text{flat}} \) and \( \phi_{\text{DEM}} \)) which is considered equal for both image acquisitions and derive the heights of the topography (Equation 2; ESA TM-19A, chapter 2.2; ESA TM-19B, chapter 3).

\[
\phi_{\text{DEM}} = \phi - \phi_{\text{flat}} - \phi_{\text{disp}} + \phi_{\text{atm}} + \phi_{\text{noise}}
\]  

This works best if atmospheric contributions and other noise is kept as small as possible because they are hard to estimate and if there is no elevation change \( \phi_{\text{disp}} \) between the two image acquisitions. It is therefore advisable to use images from the dry season and with a suitable perpendicular baseline. More hints on the selection of suitable image pairs for InSAR DEM generation are given in ESA TM-19B, chapter 1.3). This source names an optimum perpendicular baseline of 150 - 300 m, but Sentinel-1 was mainly designed for differential interferometry (DInSAR, ref1, ref2), so image pairs with short temporal baselines (6 - 12 days at best) and perpendicular baselines above 100 meters are hard to find.

Besides the interferometric phase, the coherence between the master and the slave image is estimated as an indicator for the quality of the phase information. Basically, it shows if the images have strong similarities and are therefore usable for interferometric processing. Loss of coherence can produce poor interferometric results and is caused by temporal (over vegetation and water bodies), geometric (errors or inaccuracies in the orbit metadata) and volumetric decorrelation (potential scattering mechanisms of voluminous structures, such as complex vegetation or dry surfaces).
Because of the predominantly short perpendicular baselines and the comparably quick decorrelation of C-band SAR data, repeat-pass interferometry for DEM generation is challenging, especially over vegetated areas. So please be aware that, despite the higher spatial resolution, phase decorrelation will lead to errors and the resulting elevation data is not of better quality than of freely available DEMs, such as SRTM or AW3D30, in most cases.

Coherence is calculated as a separate raster band and shows how similar each pixel is between the slave and master images in a scale from 0 to 1. Areas of high coherence will appear bright. Areas with poor coherence will be dark. In the image, vegetation is shown as having poor coherence and buildings have very high coherence.

To compute the interferogram and the coherence bands, apply the Interferogram Formation operator (under Radar > Interferometric > Products). Select the coregistered stack you generated in the previous step as an input and make sure to check the boxes:

- **Subtract flat-earth phase**: The flat-earth phase is the phase present in the interferometric signal due to the curvature of the reference surface. The flat-earth phase is estimated using the orbital metadata information and subtracted from the complex interferogram.
- **Include coherence estimation**: This produces a coherence band in the output calculated based on a window of 10x3 pixels in range/azimuth direction based on equation 1.13 in ESA TM-19C.

Please do not check “Subtract topographic phase”, because this is the information if interest.

The resulting product will contain the interferogram (Phase_ifg_IW...) and the coherence (coh_IW...) as separate bands (Figure 15). Double click them to check for their quality.
The interferogram is displayed in a rainbow color scale ranging from \(-\pi\) to \(+\pi\) and contains variations from topography, atmosphere and potential surface deformation (considered zero). The patterns, also called “fringes” represent a full \(2\pi\) cycle and appear in an interferogram as cycles of arbitrary colors, with each cycle representing half the sensor’s wavelength.

To derive a DEM of sufficient quality, these fringes must be visible throughout the entire image. Areas of phase decorrelation appear as noise in the interferogram.

The coherence shows the areas where the phase information is coherent, which means that it can be used to measure topography (as in this tutorial) or deformation (includes removing the topographic phase). While large areas show high coherence (above 0.6), river valleys are dark and have low coherence (below 0.3). Accordingly, phase information over low coherence areas will not produce correct elevation measures. If low coherence areas are too dominant in the image, the later unwrapping will fail and produce faulty or random results.

Figure 15: Interferogram (top) and coherence (bottom)

Figure 16: Histogram of interferogram (left) and coherence (right)
**TOPS Deburst**

To remove the seamlines between the single bursts, the *S-1 TOPS Deburst operator* (under *Radar > Sentinel-1 TOPS*) is applied to the interferogram product. It does not require any user input (Figure 17). The output contains the same bands as the input, but with merged bursts according to their zero Doppler time. More information on this step is provided in the *Sentinel-1 User Guide*.

![TOPS Deburst and Goldstein phase filtering](image)

Figure 17: TOPS Deburst (left) and Goldstein phase filtering (right)

**Goldstein Phase Filtering**

Interferometric phase can be corrupted by noise from temporal and geometric decorrelation, volume scattering, and other processing errors. Phase information in decorrelated areas cannot be restored, but the quality of the fringes existing in the interferogram can be increased by applying specialized phase filters, such as the Goldstein filter which uses a Fast Fourier Transformation (FFT) to enhance the signal-to-noise ratio of the image. This is required for a proper unwrapping in the subsequent step. A detailed description of this filter and its parameters is given in the publication of *Goldstein & Werner (1998)*.

Apply the Goldstein Phase Filtering (under *Radar > Interferometric > Filtering*) to the debursted image. The output is a filtered phase image, the coherence is not affected.

![Interferogram before and after Goldstein phase filtering](image)

Figure 18: Interferogram before (left) and after (right) Goldstein phase filtering
**Create a Subset**

During the previous processing steps, empty pixels at the edge of the interferogram might have been introduced, for example in areas which are not covered by both input images. To crop these areas, the *Subset* (under Raster) operator can be used. This not only reduces the size of the processed data in the subsequent steps, but also prevents later unwrapping errors. Select the filtered product, start the Subset operator, enter the following pixel coordinates (Figure 19), and confirm with *Run*.

- Scene start X: 1000
- Scene start Y: 50
- Scene end X: 25000
- Scene end Y: 2750

![Subset operator](image)

**Figure 19: Creating a subset**

![Interferogram before and after subset](image)

**Figure 20: Interferogram before (top) and after (bottom) creating the subset**
A new product is shown in the *Product Explorer*, starting with `subset_0_of_` for each subset. These products are only of temporary nature and lost after SNAP is closed. To permanently store them, right-click on the products, select **Save Product As…** and save them in BEAM DIMAP format under the name `20190708_20190702_split_Orb_Stack_esd_ifg_deb_flt_subset`.

**Phase Unwrapping**

In the interferogram, the interferometric phase is ambiguous and only known within the scale of $2\pi$. To be able to relate the interferometric phase to the topographic height, the phase must first be unwrapped. The altitude of ambiguity is defined as the altitude difference that generates an interferometric phase change of $2\pi$ after interferogram flattening.

Phase unwrapping solves this ambiguity by integrating phase difference between neighboring pixels. After deleting any integer number of altitudes of ambiguity (equivalent to an integer number of $2\pi$ phase cycles), the phase variation between two points on the flattened interferogram provides a measurement of the actual altitude variation (Figure 21). Accordingly, unwrapped results should be interpreted as a relative height/displacement between pixels of two images.

For optimal unwrapping results it is recommended to filter the interferogram as done in the previous step and eventually apply multi-looking (under Raster > SAR Utilities). As the fringe patterns are quite fine scaled (Figure 18), no multi-looking is applied in this case.

The quality and reliability of unwrapped results very much depends on the input coherence. Reliable results can only be expected in areas of high coherence. Although no definite threshold exists, a minimum coherence of 0.3 is suggested.

Unwrapping in SNAP follows three distinct steps:

1. **Export** of the wrapped phase (and definition of the parameters)
2. **Unwrapping** of the phase (performed outside SNAP by snaphu)
3. **Import** of the unwrapped phase back into SNAP

Because snaphu is an independent software (see under the section “Install snaphu” at the beginning of this document), the unwrapping is executed outside SNAP, but the plugin allows to call this execution, so no command line processing is required any longer.
Depending on the capabilities of the system, the unwrapping can take a considerable amount of time. However, snaphu supports multi-threading which means that the computation can be distributed over multiple processor cores. This has to be defined during the export.

**Export**

The Export operator (under Radar > Interferometric > Unwrapping) converts the interferogram (as the wrapped phase) into a format which can be read by snaphu. Furthermore, a couple of parameters can be selected which affect the unwrapping process and stored in a configuration file which is accessed by snaphu.

The source product is the subset created in the previous step. In the SnaphuExport tab, select your working directory as the target folder (here: C:\Temp\S1_InSAR_DEM). If the selection of the directory does not work, simply copy and paste the path of your working directory into the text field. Select TOPO as Statistical-cost mode and select 200 pixels for Row Overlap and Column Overlap. Depending on the number of processors of your computer, you can also increase the Number of Processors variable.

Note: You can neglect the eventual error message (Error: [NodeId: SnaphuExport Please add a target folder]. It will go away once you switch tabs or hit Run, as long as you have entered a valid target folder.

To learn about the meaning and impact of all parameters, please consult the official documentation.

![Figure 22: Snaphu export](image)

Hit Run to start the export. A directory is created in your working directory with the same name as the product you selected as an input (here: 20190708_20190702_split_Orb_Stack_ead_ifg_deb_flt_subset). Inside this folder, you find:

- **the coherence**: image (*.img) and metadata (*.hdr)
- **the wrapped phase**: image (*.img) and metadata (*.hdr)
- **the unwrapped phase**: only the metadata (*.hdr), because the image (*.img) is first to be created by snaphu in the next step.
- **a configuration file** (snaphu.conf) containing the parameters defined in the export operator
Unwrapping with snaphu

Once the product is exported correctly, the unwrapping can be started from within SNAP, by calling the Snaphu-unwrapping operator (under Radar > Interferometric > Unwrapping). As an input product, select the subset which was created before the export from the drop-down menu. For the output folder in the Processing Parameters tab you can activate Display execution output and select the folder which was created during the export (here: 20190708_20190702_split_Orb_stack_esd_ifg_deb_flt_subset). To start the unwrapping, click Run. SNAP then sends the command stored in snaphu.conf to the snaphu.exe which creates the raster image belonging to the unwrapped phase metadata.

Figure 23: Unwrapping with the snaphu plugin

Note: If the tool is not executed by clicking Run, go to Manage External Tools in the Tools menu. Select “Snaphu-unwrapping” and click Edit the selected operator to open the configuration and enter the export directory in the variable USERPROFILE under the System Variables tab. Confirm with OK and start the Snaphu-unwrapping operator again.

Figure 24: System variables of the snaphu plugin
Note that unwrapping can take a considerable amount of time. To break the raster into smaller chunks, snaphu divides it by standard into 10 rows and 10 columns, leading to a total of 100 tiles to be unwrapped. These tiles are merged afterwards based on the selected pixel overlap (here 200 pixels). A progress bar will inform you about the remaining time. The calculation is completed when the progress reaches 100% and the output states “Finished tool execution in … seconds”. You can then close the operator.

Alternative option: If the unwrapping does not work with the plugin from within SNAP, snaphu can also be started from the command line. It can be downloaded from the following page which also contains instruction for its manual execution: https://step.esa.int/main/third-party-plugins-2/snaphu/

**Import**

The opened unwrapped phase does not have any metadata or geocoding. The Snaphu import (under Radar > Interferometric > Unwrapping) converts the it back into the BEAM DIMAP format and adds the required metadata from on the wrapped phase product as they have the same geometry. The Snaphu import needs the following tabs:

- **1-Read-Phase**: Here, you select the subset of the interferogram (before the export) from the drop-down menu.
- **2-Read-Unwrapped-Phase**: Select the icon to open a file menu and navigate to the export directory. Select the *.hdr file of the unwrapped phase (here UnwPhase_ifg_[...].hdr). Note: The error message will then vanish if you proceed to the next tab.
- **3-SnaphuImport**: Leave the option “Do NOT save Wrapped interferogram in the target product” unchecked, because it is required in the later step.
- **4-Write**: To store the imported unwrapped band in a separate product (recommended), add '_unw' to the output name (here: 20190708_20190702_split_Orb_Stack_esd_ifg_deb_flt_subset_unw) and click Run.

A new product is added to the Product Explorer which contains the wrapped interferogram (Phase_ifg_IW...), the coherence (coh_IW ...) and the unwrapped phase generated with snaphu (here: UnwPhase_ifg_IW2_VV_08Jul2019_02Jul2019)

Double click on the unwrapped phase to see if the unwrapping was successful. It should be a smooth raster with little variation except for the areas of expected deformation (Figure 25). All fringe patterns are summarized to absolute changes (Figure 21). Unwrapping errors can occur in areas of low coherence and in urban areas with many vertical objects.

If you notice strange grid-like patterns in your unwrapped results, you can change the amount of tile columns and rows in the export (or directly in the snaphu.conf file) and run the unwrapping again. Just make sure you delete the unwrapped phase (UnwPhase_ifg_[...].img) and the temporary files in the export directory before you restart the unwrapping. Sometimes it is also favorable to switch the statistical cost-mode from DEFO to SMOOTH or the initial method from MCF to MST and compare the outputs.
Phase to Elevation

The unwrapped phase is now a continuous raster but not yet a metric measure. To convert the radian units into absolute heights, the Phase to Elevation operator (under Radar > Interferometric > Products) is applied. It translates the phase into surface heights along the line-of-sight (LOS) in meters. The LOS is the line between the sensor and a pixel. A DEM is used to put the elevation values in the correct level.

In the Processing Parameters tab, select SRTM 1Sec HGT (AutoDownload) as input DEM.

The operator is applied to the unwrapped phase which was imported in the last step. It produces an output which looks similar to the unwrapped phase (slightly different predefined color ramp), but now each pixel has a metric value indicating its height above sea level.

You can plot a Histogram to check the frequency distribution of the values (Figure 27).
Figure 27: Histogram of the elevation raster

Note: The original phase and coherence bands are not automatically copied into the resulting raster of the Phase to Elevation operator. If they are needed in the final product, they can be added via the Band Maths operator (right-click on the elevation product and select Band Maths).

Call the new raster which is to be generated coherence and uncheck the “Virtual” option (Figure 28, left). Open the Band Maths Expression Editor by clicking Edit Expression. You can now switch between products which have the same dimensions (rows and columns) in the Band Maths Expression Editor and double-clicking the coherence band of a previous product to add it to the expression window (Figure 28, right). Confirm with OK (twice) to apply the calculation.

The coherence band is now part of the elevation product. Save it by selecting File > Save Product in the menu.

Figure 28: Transfer of bands between products
You can digitize a line and use the Profile Plot tool to visualize single elevation patterns and their value ranges (Figure 29). This is also a good way to check also the amount of noise in the lower coherence areas. Smooth lines indicate good results while sawtooth patterns are often caused by phase decorrelation.

![Profile Plot](image)

**Figure 29: Profile plot the created elevation**

**Terrain Correction**

Terrain Correction will geocode the image by correcting SAR geometric distortions using a digital elevation model (DEM) and producing a map projected product.

Geocoding converts an image from slant range or ground range geometry into a map coordinate system. Terrain geocoding involves using a Digital Elevation Model (DEM) to correct for inherent geometric distortions, such as foreshortening, layover and shadow (Figure 30). More information on these effects is given in the ESA radar course materials.

![Geometric distortions](image)

**Figure 30: Geometric distortions in radar images (Braun 2019)**
Open the Range Doppler Terrain Correction operator (under Radar > Geometric > Terrain Correction). Select the elevation product as an input in the first tab.

In the Processing Parameters tab, select SRTM 1Sec HGT (AutoDownload) as input DEM.

If you want to export the data as a KMZ file to view it in Google Earth WGS84 must be selected as Map Projection. It is based on geographic coordinates (latitude and longitude). For the later use in a geographic information system (GIS) a metric map projection, such as UTM (Automatic) could be selected as well.

If no Source Band is selected, all bands of the input product are geometrically corrected.

If you want to compare the quality of the InSAR DEM, you can select DEM as a further output. This writes the SRTM data used for Terrain Correction to a separate elevation band. The Sentinel-1 DEM will then be named elevation_VV and the SRTM data is named elevation. This option is, however, just for comparison and not mandatory.

Click on Run to start the terrain correction. SNAP now establishes a connection to an external elevation database to download all SRTM tiles required to fully cover the input dataset.

Double click on the output to view the geocoded elevation raster (Figure 32).
**Export to Google Earth**

All geocoded products (projected to WGS84) can be exported as a KMZ file to view them in [Google Earth](https://earth.google.com).

Select a suitable color scale and color ramp in the *Color Manipulation* tab and then chose *File > Export > Other > View As Google Earth KMZ*.

Select an output directory and a suitable filename and confirm with **Save**. Open the kmz file in Google Earth to view the location of the elevation patterns on the satellite image base map (Figure 33).

![Figure 33: Result exported to Google Earth](image-url)
Comparison with SRTM

Open the file `elevation_vv.img` (inside the `_TC.data` folder) into a GIS (e.g. QGIS) and compute a hillshade representation. You might need to set the z-value to 0.000015 (because data projected in WGS84 is based on degrees and the height is given in meters). The coherence layer will give you an indication on where your data is of good quality and where there can be phase errors: This is mainly within agricultural and urban areas, as well as at slopes in the radar shadow (facing southeast).

![Hillshade of S1 DEM (top) and SRTM (middle); and coherence (bottom)](image)

Figure 34: Hillshade of S1 DEM (top) and SRTM (middle); and coherence (bottom)
# Troubleshooting

<table>
<thead>
<tr>
<th>Problem</th>
<th>Example</th>
<th>Explanation / Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>The interferogram looks bad. No fringes are visible</td>
<td><img src="image1.png" alt="Example Image" /></td>
<td>Decorrelation of the phase, probably because of surface changes between both acquisitions (vegetation cover). Things to try: Search image pairs  - with a shorter temporal baseline  - from the dry season  - with a larger perpendicular baseline (above 150) Please also see the hints in section “Selection of suitable images”</td>
</tr>
<tr>
<td>A trend (ramp) superimposes the topographic fringes</td>
<td><img src="image2.png" alt="Example Image" /></td>
<td>The estimation of the flat-earth phase was not correct. Things to try (in the Interferogram Generation step):  - increase the Degree of flat-earth polynomial  - increase the Number of flat-earth estimation points  - increase the Orbit interpolation degree</td>
</tr>
<tr>
<td>Strange phase jumps in the interferogram</td>
<td><img src="image3.png" alt="Example Image" /></td>
<td>Some slopes might be too steep for the given wavelength. Things to try:  - Use images of a different flight direction: ascending instead of descending (or vice versa)  - Use images with a larger perpendicular baseline. Please also see the hints in section “Selection of suitable images”</td>
</tr>
<tr>
<td>The interferogram contains straight lines with phase jumps</td>
<td><img src="image4.png" alt="Example Image" /></td>
<td>During the unwrapping, the total raster is divided into smaller parts (tiles), by standard 10x10. They are merged in the end. If this fails, such lines appear: Things to try: Repeat the unwrapping  - with a smaller number of tiles  - with larger tile overlap  - with SMOOTH instead of TOPO  - with MST instead of MCF</td>
</tr>
<tr>
<td>The Goldstein phase filter introduces cross-like patterns (often over urban areas)</td>
<td><img src="image5.png" alt="Example Image" /></td>
<td>If the moving window is dominated by a single bright pixel, the FFT of the Goldstein phase filter is blurred by sidelobes which cause these patterns. Things to try:  - Reduce the Adaptive Filter Exponent to 0.3 or lower.</td>
</tr>
</tbody>
</table>
For more tutorials visit the Sentinel Toolboxes website

http://step.esa.int/main/doc/tutorials/

Send comments to the SNAP Forum

http://forum.step.esa.int/