Documentation – User's Guide

Differential Interferometry and Geocoding Software – DIFF&GEO

Differential Interferometry

GAMMA REMOTE SENSING

Version 1.4 – June 2013

GAMMA *Remote Sensing AG, Worbstrasse 225, CH-3073 Gümligen, Switzerland*
tel: +41-31-951 70 05, fax: +41-31-951 70 08, email: gamma@gamma-rs.ch

Table of contents

List of acronyms

DEM	DIGITAL ELEVATION MODEL
DIFF&GEO	DIFFERENTIAL INTERFEROMETRY AND GEOCODING SOFTWARE
ERS	EUROPEAN REMOTE SENSING (SATELLITE)
ESA	EUROPEAN SPACE AGENCY
FFT	FAST FOURIER TRANSFORM
ISP	INTERFEROMETRIC SAR PROCESSOR
LS	LEAST SQUARES
SAR	SYNTHETIC APERTURE RADAR
SLC	SINGLE LOOK COMPLEX

1. Introduction

The GAMMA Differential Interferometry and Geocoding Software (DIFF&GEO) is a collection of programs designed to support the SAR Differential Interferometric data processing as well as geocoding between range-Doppler coordinates and map projections. The reason for inclusion of these quite different processes into one software module is that geocoding capability is required for 2-pass differential interferometry. Programs in the DIFF&GEO allow transformation of DEM data into range-Doppler coordinates, transformation of data in radar geometry to map coordinates, precision measurement of offsets between intensity images and calculation of polynomial models of these offsets, simulation of interferometric phase, generating linear combinations of interferograms, stacking of interferograms, generating of a lookup table to map one image into another and resampling of one image into the geometry of another using this lookup table.

In this Manual the programs and the processing steps that support differential interferometric processing with the DIFF&GEO module are described. Programs and processing steps required in the geocoding step can be found on the DIFF&GEO User's Guide on Geocoding and Image Registration. In addition, differential interferometric processing requires the availability of at least an interferogram, baseline information and, in some cases, of a phase unwrapping stage. For this reason, the programs of the ISP module for interferometric processing are required in differential interferometric processing.

Section 2 provides a brief reminder of the several procedures for differential interferometric processing and a flow chart summarizing these procedures. Sections 3 to 6 illustrate the processing steps and the individual programs for each procedure. Section 7 illustrates further processing possibilities related to the mitigation of atmospheric phase component in a differential interferogram. Section 8 illustrates the programs that allow the retrieval of the displacement from a differential interferogram.

2. Differential Interferometry

The aim of differential interferometric processing is the separation of the topographic and the displacement term in an interferogram. For a theoretical background on differential interferometric processing, it is referred to the Documentation-Theory on Interferometric SAR Processing.

To identify the displacement component, the topographic phase has to be removed. Depending whether a DEM is available or not, we speak of 2-pass differential interferometry, otherwise we speak of 3- or 4-pass differential interferometry. The approaches to obtain a differential interferogram differ depending not only whether a DEM is available or not but also if the phase unwrapping operation is required. If the aim is instead to identify the topographic component, the differential phase has to be removed. This can be done by combining complex interferogram and scaling so that phase noise is reduced and an effective baseline larger than the original baselines is obtained. Table 1 summarizes the requirement set by each procedure.

Table 1. Approaches of differential interferometry.

Differential interferometric approach	Dataset	DEM	Unwrapping
2-pass differential interferometry	InSAR pair and DEM	External	No
3-pass differential interferometry	3 SAR images (= 2 InSAR pairs)	From one InSAR pair	Yes
4-pass differential interferometry	4 SAR images (= 2 InSAR pairs)	From one InSAR pair	Yes
Combination of complex interferograms	2 InSAR pairs	No	No

In all cases the interferogram which contains the differential phase effect (overlaid with the phase due to scene topography) may either be unwrapped before the formation of the differential interferogram or not. The first approach results directly in the unwrapped differential phase. The second approach in a complex differential interferogram which may be filtered and unwrapped after the phase subtraction. Overall phase trends may appear in differential interferograms as a result of inaccurate baseline (respectively orbit) information. Such phase trends may either be removed in the phase subtraction step by using least squares fitting techniques to adjust the scaling of the reference phase image, or, the complex differential interferogram may be flattened using FFT techniques for the estimation of the remaining overall phase trend.

Figure 1 illustrates the processing methods for differential interferometry. Sections 3.1 and 3.2 deal with different processing methods in the case of 2-pass differential interferometry (method 1 and 2 in Figure 1). More specifically, Section 3.1 deals with method 1 in which the interferogram is unwrapped before proceeding with the removal of the topographic phase, here simulated from a DEM. Section 3.2 deals with method 2 in which the interferogram is not unwrapped before the subtraction of the topographic phase simulated from the DEM. Phase unwrapping is then carried out on the differential interferogram. Sections 4 and 5 deal with different processing methods in the case of 3- and 4-pass differential interferometry. More specifically, Sections 4.1 (and 5.1) and 4.2 (and 5.2) explain methods 3 and 4 respectively, which are in some sort of way similar to methods 1 and 2. The only difference is the use of an unwrapped interferogram from an interferogram not containing the differential phase instead of the simulated phase from a DEM. Section 6 illustrates the processing steps required in method 5, which corresponds to the combination of interferograms to remove a differential phase component to obtain a topographic phase image.

Regardless of the processing method, mitigation of atmospheric phase component may be necessary before producing a displacement map or a height map. It is somehow possible to mitigate the effect of atmospheric phase due to elevation changes using a linear atmospheric model relating the unwrapped phase due to path delays to elevation. If more interferograms are available it is possible to filter them out by stacking the unwrapped phases. While differential signals are correlated, atmospheric phase distortions are random and therefore cancel out when stacking interferograms. These approaches are described in Section 7. The programs for obtaining a displacement map or a topographic map are described in Section 8.

This document includes a number of processing Examples, each dealing with one of the processing methods described in this Section. It should be remarked that parameter values provided in the processing examples presented in this document cannot be considered valid for all cases. It is possible that one or more values might have to be adapted to the specific case being processed. It is advised to look carefully at the messages printed on stdout when running each individual program. For assistance please get in contact with us (gamma@gamma-rs.ch).

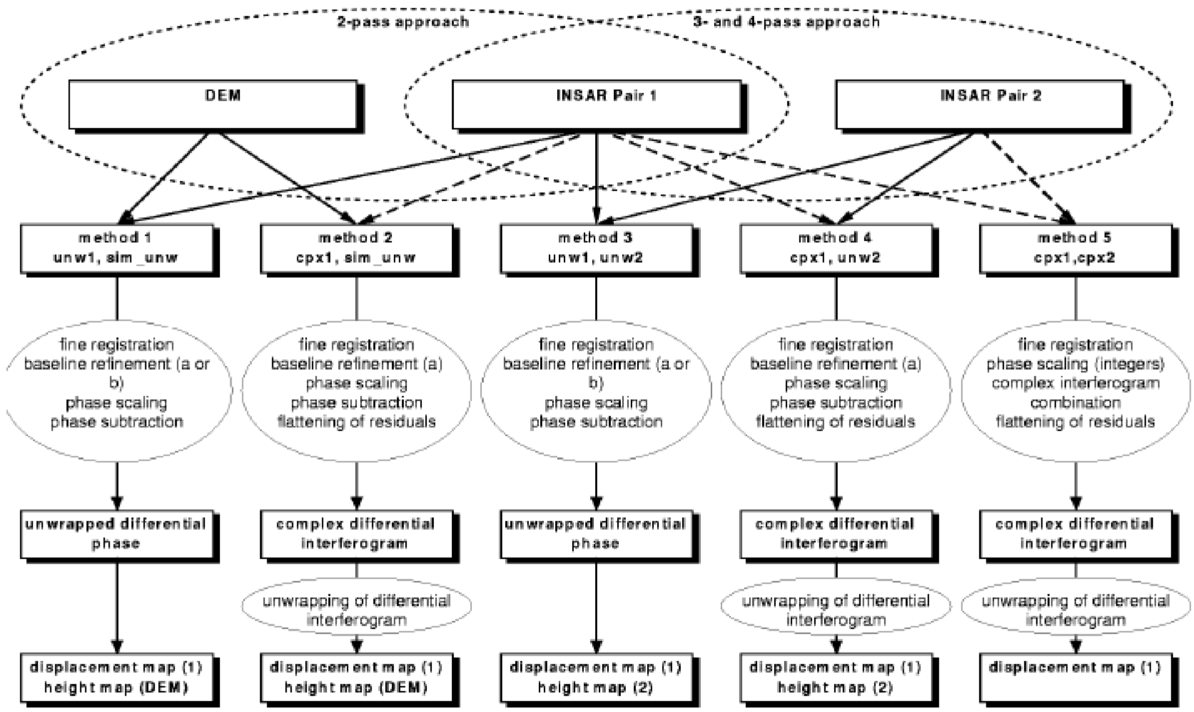


Figure 1. Flow chart for differential interferometry processing methods. The selection of the appropriate method depends on the availability of a digital elevation model (DEM) and on the capability to unwrap the interferometric phase (cpx stands for the complex interferograms, unw for the unwrapped phase image, sim_unw for the simulated unwrapped topographic phase calculated from the DEM). The processing chains for 3- and 4-pass differential interferometry are identical except that no additional registration step is required in the 3-pass approach if both interferometric pairs use the same scene as reference geometry.

3. 2-pass differential interferometry

2-pass differential interferometry is based on an interferometric image pair and a Digital Elevation Model (DEM). The DEM may either be given in a map projection, or in the slant range - azimuth geometry of the SAR image. If the DEM is given in a map projection, transformation of the DEM from map to radar geometry is necessary. The procedure for transforming an image from map to radar geometry is described in the User’s Guide on Geocoding and Image Registration. In the Examples Section a reminder on the geocoding processing steps is provided.

The basic idea of 2-pass differential interferometry is that a reference interferogram (interferogram with phase corresponding to surface topography) is simulated based on the DEM. Based on the reference SAR geometry, the interferometric baseline model, and the height map in radar geometry, the unwrapped interferometric phase corresponding exclusively to topography is calculated. In the following this phase will also be called topographic phase.

The topographic phase may either be subtracted from the unwrapped phase (resulting in the unwrapped differential phase) or from the complex interferogram (resulting in a complex differential interferogram). In the first case (method 1 in Figure 1) phase unwrapping of the original interferogram is required; in the second case (method 2 in Figure 2) phase unwrapping of the differential interferogram is required. Whether to unwrap the original interferogram or the differential interferogram depends on the image and on the distribution of the fringes. Using 2-pass differential interferometry the generation of a complex differential interferogram is very robust. The generation of the unwrapped differential phase depends on the capability to unwrap either before or after the reference phase subtraction. Especially in terrain with rugged topography the unwrapping of the differential phase (i.e. after the calculation of the phase difference) may be a much easier task than the unwrapping of the phase image which includes both phase due to topography and differential effects. For more information on phase unwrapping issues, it is referred to the Documentation of the ISP module.

In the following the processing steps for the methods 1 and 2 in 2-pass differential interferometry are described in more detail.

3.1. 2-pass differential interferometry with phase unwrapping

This processing method requires the original interferogram unwrapped. This is a real valued image obtained after phase unwrapping, i.e. what we called *.unw in the User's Guide of the ISP module. For differential interferometry the unwrapped image is assumed to be in the original SAR geometry, i.e. the curved Earth phase trend is included. This means that the interferometric processing leading to the unwrapped phase image shall be done without ellipsoidal Earth phase trend removal. This is however recommended only for small baselines. In other cases, it is recommended to unwrap the flattened interferogram first. Then, for an unwrapped phase image with removed curved Earth phase trend (i.e. the unwrapped phase of the flattened interferogram) the ellipsoidal Earth phase trend must be added back to the unwrapped interferogram using the ISP program ***ph_slope_base***.

The first step in differential interferometric processing is to simulate the unwrapped topographic and curved Earth trend fringes from the DEM. The DEM has to be transformed from map to radar geometry beforehand (see DIFF&GEO User's Guide to Geocoding and Image Registration and Example A in this document). Simulation of the interferometric fringes can be done with one of the programs ***phase_sim*** or ***phase_sim_orb***. Both programs simulate the unwrapped phase using the elevation values in the DEM and information on the baseline. In ***phase_sim*** the baseline is obtained from the baseline file of the interferometric pair (obtained with one of the programs of the ISP dedicated to baseline computation). Experience showed that the available baseline information, especially the one calculated from orbit data, may not be sufficiently accurate. In addition a linear model describing the variation of the baseline might be inadequate, especially for long data strips. In the first case a refinement step in the estimation of the baseline is required before subtracting the simulated phase from the original unwrapped interferogram (see e.g. Section 9). In the second case a possible solution is to estimate residual trends using the programs ***quad_fit*** and ***quad_sub*** (see Section 3.2). With ***phase_****sim_orb* it is possible to overcome both problems. The interferogram is simulated based on a height map and a deformation rate map, and the baseline is computed for each point using the DEM height, slant range distance, doppler centroid, and state vectors. This approach is applicable for long image strips where the linear baseline model may be inadequate and residual quadratic phase trends may still be visible after subtraction of the simulated phase.

To obtain the differential interferogram a parameter file for the differential interferogram must be generated. This is done with the program ***create_diff_par***. The (slight) scaling of the simulated unwrapped phase introduced by errors in the baseline model may be improved by least squares fitting between the simulated and real unwrapped phase image. Using a least squares fitting approach implemented in the program ***diff_ls_fit*** it is possible to optimize the phase scaling factors between the two images. The phase scaling factors are then stored in the DIFF_par file, i.e. the parameter file for the differential interferometric processing (see also Example A). Notice, that this technique may not work appropriately for ellipsoidal Earth phase trend removed data. At the moment, this least squares fitting approach to determine improved phase scaling functions is supported only for the approach based on the unwrapped phase. Nevertheless, flattening of the complex differential interferogram obtained in the approach based on the complex interferogram corresponds to bi-linear phase scaling.

By applying the phase scaling factors to the simulated and real unwrapped interferograms the unwrapped differential interferogram can be generated. This is done with the program ***diff_ls_unw***. The differential phase image is real-valued (since it is unwrapped) and is in the SAR range-Doppler geometry. This unwrapped differential interferometric phase image, or the corresponding displacement map, can be geocoded using the geocoding lookup table obtained when determining the transformation between map and radar geometry. For more details it is referred to Example A.

3.2. 2-pass differential interferometry without phase unwrapping

This processing method requires the original interferogram. This is a complex valued image obtained after cross-correlation of the two SLC images, i.e. what we called *.int in the User's Guide of the ISP module. For differential interferometry the interferogram is assumed to be in the original SAR geometry, i.e. the curved Earth phase trend is included. Compared to the previous approach phase unwrapping of the original interferogram is not needed, which makes this procedure to obtain a differential interferogram more robust. As a matter of fact, phase unwrapping is only required once the differential interferogram (complex) has been obtained. In this image the fringe pattern is much easier to unwrap compared to the original interferogram. It can be applied even if the interferometric phase could not be successfully unwrapped. As a draw back, on the other side, the scaling of the topographic phase due to errors in the baseline model cannot be improved with the LS-fitting approach.

The first step in differential interferometric processing is to simulate the unwrapped topographic phase (including the curved Earth trend) from the DEM. This is done with the program ***phase_sim***. It shall be noticed that the DEM has been transformed from map to radar geometry (see the DIFF&GEO User's Guide on Geocoding and Image Registration and Example B in this document). The program requires baseline information to simulate the interferometric fringes.

To obtain the differential interferogram a parameter file for the differential interferogram must be generated. This is done with the program ***create_diff_par***. Then the simulated interferogram needs to be subtracted from the original interferogram. This can be done in two ways:

- With the program ***sub_phase*** the unwrapped simulated phase is subtracted from the original interferogram, returning the wrapped differential interferogram
- With the program ***SLC_diff_intf*** it is possible to generate the differential interferogram directly from the co-registered SLC images (i.e. no need of generating an interferogram)

and the unwrapped simulated phase. The program applies range-adaptive common band filtering and returns the wrapped differential interferogram. It is important that the range and azimuth looks and dimensions of this simulated interferogram are the same as the output interferogram. This is a more advanced procedure. Its use is particularly recommended when processing to interferometry data over hilly and mountainous terrain. This program in fact uses local slope information to avoid spatial decorrelation induced by the non-flat topography.

Typically, the available baseline information, especially the one calculated from orbit data, may not be sufficiently accurate. Hence a refinement step is required to avoid a scaling factor on the differential interferogram.

The method described in Section 3.1. cannot be used since both interferograms (original and simulated) are wrapped. For this reason another method for correcting the scale trend has to be applied. FFT is applied to the resulting interferogram (with one of the programs ***base_init*** or ***base_est_fft***). In this way a residual baseline component is determined. The residual baseline model is then applied to correct for the initial baseline model using the program ***base_add***. The refined baseline model is applied to re-simulate the interferometric phase from the DEM using the program ***phase_sim*** and a new differential interferogram is generated with either the program ***sub_phase*** or ***SLC_diff_intf***. If this interferogram still presents residual systematic fringes a new iteration using the sequence ***base_init/base_est_fft, base_add, phase_sim*** and ***sub_phase/SLC_diff_intf*** can be applied.

Once the final differential interferogram has been obtained, phase unwrapping (and filtering) is necessary. The differential interferogram is in SAR range-Doppler coordinates and is complex-valued. Filtering and phase unwrapping of the differential interferogram can be done using one of the methods presented in the Documentation to the ISP module.

An unwrapped interferogram might show still some residual phase components that are not related to geophysical events but rather to topographic or system phase components, i.e. baseline-related phase effects in the form of ramps that were not entirely removed during the generation of the interferogram. This might be the case for example for image pairs with significant variations of the baseline along-track due to squinted orbits. The DIFF&GEO module includes the program ***quad_fit*** that allows the estimation of a 2-D quadratic model phase function from a differential interferogram. With the program ***quad_sub*** it is then possible to subtract the quadratic model phase function from the differential interferogram.

Finally, the unwrapped differential interferometric phase image, or the corresponding displacement map, can be geocoded using the geocoding lookup table obtained when determining the transformation between map and radar geometry. For more details it is referred to Example B.

4. 3-pass differential interferometry

3-pass differential interferometry is based on three SAR images, i.e. two interferometric image pairs having one image in common or, in other words, the same reference geometry.

One of the pairs is used to estimate the topographic phase. As a consequence, this pair should optimally be acquired with a short acquisition time interval (to maximize the degree of coherence) and a rather large interferometric baseline (to increase the sensitivity of the interferometric phase to topography as compared to differential effects and heterogeneity in the atmospheric path delay). As this pair is used as reference to estimated the topographic phase it should not include the coherent displacement to be investigated.

The other pair has to consist of one image before and one after the coherent displacement. To optimize the sensitivity to the differential effects the baseline should be as small as possible. In the selection of the acquisition time interval the decreasing of the degree of coherence with time and the history of the investigated coherent displacement have to be considered.

The 3-pass approach requires successful phase unwrapping of both interferograms. This is however not an absolute requirement for 3-pass differential interferometry (see also Section 6 on complex combination of interferograms without phase unwrapping), but it can, if available, be used to improve the scaling of the topographic phase.

As for 2-pass differential interferometry, the interferogram containing the displacement can be either unwrapped (real valued interferogram) or wrapped (complex valued interferogram). The processing methods that will allow generating the differential interferogram correspond to method 3 and 4 in Figure 1. In the following the processing steps for the methods 3 and 4 are described in more detail.

4.1. 3-pass differential interferometry with phase unwrapping

This processing method is similar to the corresponding one for 2-pass differential interferometry with phase unwrapping (Section 3.1).

The processing requires both the original interferogram containing the displacement (here referred to as differential pair) and the interferogram containing the topographic information (here referred to as topographic pair) in unwrapped format. The unwrapped interferograms are real valued image obtained after phase unwrapping, i.e. what we called *.unw in the User's Guide of the ISP module.

For differential interferometry the unwrapped differential pair is assumed to be in the original SAR geometry, i.e. the curved Earth phase trend is included. This means that the interferometric processing leading to the unwrapped phase image shall be done without ellipsoidal Earth phase trend removal. This is however recommended only for small baselines. In other cases, it is recommended to unwrap the flattened interferogram first. Then, for an unwrapped phase image with removed curved Earth phase trend (i.e. the unwrapped phase of the flattened interferogram) the ellipsoidal Earth phase trend must be added back to the unwrapped interferogram using the ISP program ***ph_slope_base***.

Also the unwrapped topographic interferogram shall include the curved Earth trend. If it is available in flattened format (i.e. it contains only topographic fringes), the curved phase Earth phase trend must be re-inserted to obtain the unflattened unwrapped topographic interferogram. This is done with the program ***ph_slope_base***.

To obtain the differential interferogram a parameter file for the differential interferogram must be generated. This is done with the program ***create_diff_par***. With the unwrapped phase images of the differential pair and the topographic pair, the scaling factors determined by the different baselines of the two image pairs have to be determined. This can be done using the least squares fit approach in the program ***diff_ls_fit***. The program determines the scaling factor for the phase, which is then written to the DIFF_par file that contains all parameters relative the differential interferometric processing.

One of the options in this program is the ability to mask out areas with known motion, or unwrapping errors from contributing to the least squares fit. The overlay file that is used to do this is in the SUNraster or bmp format and is typically created from the unwrapped interferogram. Regions in the raster image set to 0, using an image editing program, such as xv are then excluded. This can significantly improve the least squares fit and accuracy of the differential interferogram.

Using the phase scaling factors, the differential interferogram (unwrapped) can now be generated. This is done with the program ***diff_ls_unw***. The resulting image in real valued and in SAR range-Doppler geometry.

Another approach that can be used in 3- and 4- pass differential interferometry is to scale the unwrapped phase of an interferogram used as reference for the topographic phase of the differential interferogram. This can be done with the program ***scale_base***. The location dependent phase scale factor is calculated from the baselines of the interferogram used as topographic reference and the differential interferogram. After scaling the real valued scaled unwrapped phase is subtracted from the differential interferogram with the program ***sub_phase***.
The differential interferometric phase image obtained with one or the other method can now be converted to displacement. The differential phase and/or the displacement map can be geocoded. Contrarily to 2-pass differential interferometry, here the geocoding lookup table must still be obtained. It is referred to the DIFF&GEO User’s Guide on Geocoding and Image Registration for more information on how to geocode the differential interferogram.

Example C shows 3-pass differential interferometric processing with phase unwrapping.

4.2. 3-pass differential interferometry without phase unwrapping

This processing method requires the original interferograms for the differential pair and the unwrapped interferogram for the topographic pair. The original interferogram is a complex valued image obtained after cross-correlation of the two SLC images, i.e. what we called *.int in the User’s Guide of the ISP module. For differential interferometry the interferogram is assumed to be in the original SAR geometry, i.e. the curved Earth phase trend is included.

Compared to the previous approach phase unwrapping of the original interferogram is not needed, which makes this procedure to obtain a differential interferogram more robust. As a matter of fact, phase unwrapping is only required once the differential interferogram (complex) has been obtained. In this image the fringe pattern is much easier to unwrap compared to the original interferograms. Phase unwrapping is however required for the topographic interferogram. This interferogram shall contain the curved Earth component. If it is not included, it can be added back with the program ***ph_slope_base***.

To obtain the differential interferogram a parameter file for the differential interferogram must be generated. This is done with the program ***create_diff_par***. To obtain the differential interferogram the program ***diff_ls_unw*** is used. By setting the appropriate command flag, the program applies the phase correction calculated from the unwrapped topographic data to the original complex interferogram. The advantage of this is that there are by definition, no unwrapping errors and no excluded areas in the differential interferogram. The differential interferogram is at this stage wrapped, i.e. is complex-valued. To obtain the unwrapped differential interferogram, one of the unwrapping methods presented in the User's Guide of the ISP module shall be used.

The differential interferometric phase image can now be converted to displacement. The differential phase and/or the displacement map can be geocoded. Contrarily to 2-pass differential interferometry, here the geocoding lookup table must still be obtained. It is referred to the DIFF&GEO User's Guide on Geocoding and Image Registration for more information on how to geocode the differential interferogram.

5. 4-pass differential interferometry

For the 4-pass differential interferometric approach two independent SAR image pairs are required.

One of the pairs is used to estimate the topographic phase. As a consequence, this pair should optimally be acquired with a short acquisition time interval (to maximize the degree of coherence) and a rather large interferometric baseline (to increase the sensitivity of the interferometric phase to topography as compared to differential effects and heterogeneity in the atmospheric path delay). As this pair is used as reference to estimated the topographic phase it should not include the coherent displacement to be investigated.

The other pair has to consist of one image before and one after the coherent displacement. To optimize the sensitivity to the differential effects the baseline should be as small as possible. In the selection of the acquisition time interval the decreasing of the degree of coherence with time and the history of the investigated coherent displacement have to be considered.

The only difference with respect to 3-pass differential interferometry is that a pair of images independent from the differential pair is used for the generation of the topographic phase. This means that the processing steps described in Sections 4.1 and 4.2 (with and without phase unwrapping of the differential pair) apply also to 4-pass differential interferometry. The only step required prior to differential processing is the resampling of the two interferograms to the same (reference) geometry.

Below details to 4-pass differential interferometric processing using either the unwrapped or the wrapped interferogram containing the differential component are illustrated.

5.1. 4-pass differential interferometry with phase unwrapping

The processing requires both the original interferogram containing the displacement (here referred to as differential pair) and the interferogram containing the topographic information (here referred to as topographic pair) in unwrapped format. The unwrapped interferograms are real valued images obtained after phase unwrapping, i.e. what we called *.unw in the User's Guide of the ISP module.

For differential interferometry the unwrapped differential interferogram is assumed to be in the original SAR geometry, i.e. the curved Earth phase trend is included. This means that the interferometric processing leading to the unwrapped phase image shall be done without ellipsoidal Earth phase trend removal. This is however recommended only for small baselines. In other cases, it is recommended to unwrap the flattened interferogram first. Then, for an unwrapped phase image with removed curved Earth phase trend (i.e. the unwrapped phase of the flattened interferogram) the ellipsoidal Earth phase trend must be added back to the unwrapped interferogram using the ISP program ***ph_slope_base***.

Also the unwrapped topographic interferogram shall include the curved Earth trend. If it is available in flattened format (i.e. it contains only topographic fringes), the curved phase Earth phase trend must be re-inserted to obtain the unflattened unwrapped topographic interferogram. This is done with the program ***ph_slope_base***.

To resample the two interferograms to the same reference geometry, e.g. the topographic pair to the geometry of the differential pair, the following sequence shall be used.

- Generation of a DIFF_par file describing the offsets between the geometries of the two interferograms. This is done with the program ***create_diff_par***.
- Initial estimation of offsets between the two geometries. This is done with the program ***init_offsetm***. Offsets are estimated between the SAR intensity images of the master images in the two interferograms.
- Local estimation of the offsets and generation of the offset polynomials. This is done with the programs ***offset_pwrm*** and ***offset_fitm*** respectively. The programs are applied the SAR intensity images of the master images in the two interferograms.
- Resampling of the other interferogram to the geometry of the reference interferogram. This is done with the program ***interp_real***. The nearest neighbour resampling is preferred over the interpolation approach because the unwrapped phase image may contain gaps (i.e. areas with the value equal to the NULL value 0.0).

At this stage the two interferograms are in the same geometry, hence the same processing as described for 3-pass differential interferometric processing in Section 4.1 can be applied.

With the unwrapped phase images of the differential pair and the topographic pair, the scaling factors determined by the different baselines of the two image pairs have to be determined. This can be done using the least squares fit approach in the program ***diff_ls_fit***. The program determines the scaling factor for the phase, which is then written to the DIFF_par file that contains all parameters relative the differential interferometric processing.

One of the options in this program is the ability to mask out areas with known motion, or unwrapping errors from contributing to the least squares fit. The overlay file that is used to do this is in the SUNraster or bmp format and is typically created from the unwrapped interferogram. Regions in the raster image set to 0, using an image editing program, such as xv are then excluded. This can significantly improve the least squares fit and accuracy of the differential interferogram.

Using the phase scaling factors, the differential interferogram (unwrapped) can now be generated. This is done with the program ***diff_ls_unw***. The resulting image is real valued and in SAR range-Doppler geometry.

Another approach that can be used in 3- and 4- pass differential interferometry is to scale the unwrapped phase of an interferogram used as reference for the topographic phase of the differential interferogram. This can be done with the program ***scale_base***. The location dependent phase scale factor is calculated from the baselines of the interferogram used as topographic reference and the differential interferogram. After scaling the real valued scaled unwrapped phase is subtracted from the differential interferogram with the program ***sub_phase***.

The differential interferometric phase image obtained with one or the other method can now be converted to displacement. The differential phase and/or the displacement map can be geocoded. Contrarily to 2-pass differential interferometry, here the geocoding lookup table must still be obtained. It is referred to the DIFF&GEO User's Guide on Geocoding and Image Registration for more information on how to geocode the differential interferogram.

Example D shows 4-pass differential interferometric processing with phase unwrapping.

5.2. 4-pass differential interferometry without phase unwrapping

This processing method requires the original interferograms for the differential pair and the unwrapped interferogram for the topographic pair. The original interferogram is a complex valued image obtained after cross-correlation of the two SLC images, i.e. what we called *.int in the User's Guide of the ISP module. For differential interferometry the interferogram is assumed to be in the original SAR geometry, i.e. the curved Earth phase trend is included.

Compared to the previous approach phase unwrapping of the original interferogram is not needed, which makes this procedure to obtain a differential interferogram more robust. As a matter of fact, phase unwrapping is only required once the differential interferogram (complex) has been obtained. In this image the fringe pattern is much easier to unwrap compared to the original interferograms. Phase unwrapping is however required for the topographic interferogram. This interferogram shall contain the curved Earth component. If it is not included, it can be added back with the program ***ph_slope_base***.

As for the case described in Section 5.1, the first step consists in resampling the two interferograms to the same reference geometry. For example the unwrapped topographic interferogram is resampled to the geometry of the interferogram containing the differential effects. The resampling procedure is exactly the same as the one described in Section 5.1.

At this stage the two interferograms are in the same geometry, hence the same processing as described for 3-pass differential interferometric processing in Section 4.2 can be applied.

To obtain the differential interferogram a parameter file for the differential interferogram must be generated. This is done with the program ***create_diff_par***. To obtain the differential interferogram the program ***diff_ls_unw*** is used. By setting the appropriate command flag, the program applies the phase correction calculated from the unwrapped topographic data to the original complex interferogram. The advantage of this is that there are by definition, no unwrapping errors and no excluded areas in the differential interferogram. The differential interferogram is at this stage wrapped, i.e. is complex-valued. To obtain the unwrapped differential interferogram, one of the unwrapping methods presented in the User's Guide of the ISP module shall be used.

The unwrapped differential interferometric phase image, or the corresponding displacement map, can be then geocoded. Contrarily to 2-pass differential interferometry, here the geocoding lookup table must still be obtained. It is referred to the DIFF&GEO User's Guide on Geocoding and Image Registration for more information on how to geocode the differential interferogram.

6. Combination of complex interferograms

The complex combination of interferograms was included to increase the flexibility of the DIFF&GEO software. While the other approaches depend either on the availability of a DEM or on the successful unwrapping of the interferometric phase the complex combination of interferograms can be performed without meeting these requirements.

The two basic ideas used are that the argument of the product of a complex number with the complex conjugate of a second complex number equals the difference between the arguments of the two complex numbers and that phase scaling with integer factors results in the scaling of the wrapped phase with the same integer factor.

The complex combination of an interferogram with a 120m perpendicular baseline and an interferogram with a 58m perpendicular baseline with the wrapped phase scaled by a factor of 1 and -2, for example, results in a differential interferogram with an effective baseline of 4m. The differential interferogram contains the differential phase components of the first pair minus two times the differential phase components of the second pair. The sensitivity of this differential interferogram to topography is therefore much smaller compared to the original interferograms and very small in general. If the area covered by the interferogram presents local displacements, the combined interferogram will be much more suited for detecting the displacements than any of the original interferograms.

The two complex interferograms are assumed to be in original SAR geometry, i.e. the flat Earth phase trend was not removed.

The first step when combining interferograms consists in resampling one interferogram to the geometry of the other interferogram. To resample the two interferograms to the same reference geometry the following sequence shall be used.

- Generation of a DIFF_par file describing the offsets between the geometries of the two interferograms. This is done with the program ***create_diff_par***.
- Initial estimation of offsets between the two geometries. This is done with the program ***init_offsetm***. Offsets are estimated between the SAR intensity images of the master images in the two interferograms.
- Local estimation of the offsets and generation of the offset polynomials. This is done with the programs ***offset_pwrm*** and ***offset_fitm*** respectively. The programs are applied the SAR intensity images of the master images in the two interferograms.

- Resampling of the other interferogram to the geometry of the reference interferogram. Since the interferograms are complex valued, this is done with the program ***interp_cpx***.

Once the two complex valued interferogram are in the same geometry the complex interferogram combination can be applied. The two interferograms are combined with the program ***comb_interfs***. The user shall specify the integer factors for the combination. For example if the two interferograms have baseline components perpendicular to the line of sight of 120m and 58m the integer factors +1 and -2 are selected. The effective interferometric baseline of the combined interferogram is saved to a text file.

At this stage either the effective interferometric baseline for the differential interferogram obtained from the combination of the two interferograms or a baseline determined using the program ***base_est_fft*** (of the ISP module) can be used to remove the remaining phase trend. This is done with the program ***ph_slope_base***.

Notice that with the scaling of the wrapped phase the phase noise is also scaled. Therefore the approach is limited to small integer numbers. In order to reduce the upscaling of the phase noise filtering of the complex interferograms before complex interferogram combination is recommended.

Example E shows 4-pass differential interferometric processing with phase unwrapping.

7. Mitigation of atmospheric phase component

Interferograms typically contain an atmospheric phase component, which can severely distort the differential interferogram not only because they can be present in the differential interferogram itself but also because they can be contained in the interferogram used to generated the topographic phase (this for 3- and 4-pass interferometry).

The DIFF&GEO module offers two methods to reduce the effect of atmospheric phase distortions

- Estimation of a linear phase trend with elevation
- Stacking of interferograms

Below the two methods are illustrated in more detail and the corresponding programs are introduced.

7.1. Removal of height dependent atmospheric phase

Depending on atmospheric conditions there is an altitude dependence of the atmospheric path delay with respect to altitude caused by changes in the atmospheric water vapor and pressure profiles between the acquisitions of the interferometric image pair. To determine the height dependence of the unwrapped atmospheric phase the program ***atm_mod*** is used. The program estimates the parameters of a linear model consisting of a phase constant *a0* in radians and phase slope *a1* in units of radians per meter *model(x,y) = a0 + a1*hgt(x,y)*

It is important that only phase due to atmosphere is present in the differential phase. Any areas affected by other phase components should be removed before processing.

The input is the unwrapped differential interferogram of residual phases. The output phase model has the height dependent unwrapped phase as determined from the regression. The program ***sub_phase*** can then be used to remove the modeled phase from the differential interferogram.

While a height-dependant linear trend can be removed, other atmospheric distortions are still present in the differential interferogram.

For more information on the use of the program, it is referred to the Reference Guide.

7.2. Stacking of interferograms

Stacking multiple unwrapped differential interferometric phase images allows removing uncorrelated atmospheric phase components and estimating the linear rate of differential phase. The program also calculates the standard deviation of the phase rate (sigma) relatives.
To stack a number of interferograms the program ***stacking*** shall be used.

The individual interferogram phases are weighted by the time interval in estimating the phase rate. The underlying assumption is that atmospheric statistics are stationary from one observation to the next. Hence the standard deviation of the phase rate derived from a single interferogram is proportional to *1/delta_T*. As *delta_T* increases the uncertainty in the phase rate in the individual interferogram decreases.

For more information on the use of the program, it is referred to the Reference Guide.

8. Displacement retrieval

Once an unwrapped differential interferogram is available the program ***dispmap*** can be used for surface displacement map generation.

The differential interferometric phase corresponds to the displacement along the SAR look vector. As a consequence the 3-dimensional displacement of a surface element cannot be completely described. In ***dispmap*** the user can select what type of displacement shall be computed.

Under the assumption of a predefined surface displacement direction a conversion to vertical or horizontal displacement is possible by setting the „mode“ flag as follows

0: conversion to displacement along the look vector in meters
+ signs correspond to displacement towards the sensor
For this conversion no specific assumption on the surface deformation is necessary.

1: conversion to vertical displacement in meters
+ signs correspond to increasing surface height
- signs correspond to subsidence
Vertical displacement can often be assumed in the case of subsidence

2: conversion to horizontal displacement component in ground range direction in meters
+ corresponds to decreasing ground range

To obtain a more complete view of the displacement, the programs ***dispmap_vec*** and ***dispmap_vec2*** allow the computation of the displacement vector field.

The program ***dispmap_vec*** calculates the 3D displacement field based on the indicated DINSAR based line-of-sight displacement component and the indicated direction field (along height gradient). The program ***dispmap_vec2*** calculates the 3D displacement field based on 2 DInSAR-based line-of-sight displacement components (from ascending and descending orbits). In both cases the output displacement field is expressed through the norm, the elevation angle (theta) and the orientation angle (phi). The output is the norm of the 3-D displacement vector. The displacement field can be expressed in different reference systems (e.g. elevation angle (theta) and orientation angle (phi), or easting, northing and vertical components). Besides one or two displacement observations, information on the look angle needs to be provided. The look angle can be computed with the program ***look_vector***. The motion or flow direction is indicated through the related direction angles (elevation theta and orientation phi). For the case of motion along the surface height gradient the flow direction field can be calculated based on a DEM using the program ***dem_gradient***.

9. Baseline refinement

Initial estimates of the baseline, obtained for example with the programs of the ISP module ***base_init*** or ***base_orbit***, might be inaccurate so that the differential interferogram might contain residual fringes. With the program ***base_est_fft*** (part of the ISP module) it is possible to obtain an estimate of the residual baseline component. This can now be added to the original baseline estimate with the program ***base_add*** to improve it. By addition and subtraction of baselines the baselines of other SLC pairs can be estimated. This is of interest, as larger baselines or baselines for longer time intervals may be difficult to estimate from the data itself due to low coherence.

10. Additional tools

The software offers a tool to rotate an image around its central pixel with the program ***rotate_image***. The user can select the angle of rotation.

Processing examples

In the following examples of the use of the DIFF&GEO for differential interferometry are given. The main purpose of the examples is to demonstrate typical processing sequences and to facilitate the use of the DIFF&GEO.

The selection of the appropriate approach depends on the availability of a DEM and on the feasibility of phase unwrapping. Due to often present atmospheric distortions and phase unwrapping errors (as a result of low coherence and steep slopes) the 2-pass approach is often preferred for its robustness and reliability. The 3-pass, 4-pass and the complex interferogram combination approaches are very useful alternatives.

It should be remarked that parameter values provided in the processing examples cannot be considered valid for all cases. It is possible that one or more values might have to be adapted to the specific case being processed. It is advised to look carefully at the messages printed on stdout when running each individual program. For assistance please get in contact with us (gamma@gamma-rs.ch).

Example A – 2-pass differential interferometric processing with phase unwrapping
Processing steps for the generation of a differential interferogram using two SAR images and a DEM for differential interferometric processing (with phase unwrapping)

Example B – 2-pass differential interferometric processing without phase unwrapping
Processing steps for the generation of a differential interferogram using two SAR images and a DEM for differential interferometric processing (without phase unwrapping)

Example C – 3-pass differential interferometric processing
Processing steps for the generation of a differential interferogram using three SAR images for differential interferometric processing (with phase unwrapping)

Example D – 4-pass differential interferometric processing
Processing steps for the generation of a differential interferogram using four SAR images for differential interferometric processing (with phase unwrapping)

Example E – Complex combination of interferograms
Processing steps for the generation of a displacement map using complex combination of interferograms (no phase unwrapping required)

A. 2-pass differential interferometric processing with phase unwrapping

For 2-pass differential interferometric approach a SAR image pair and a DEM (in map coordinates) are required. The 2-pass approach presented in this example requires, in addition, the unwrapped interferometric phase of the image pair (not the differential phase). This is not an absolute requirement for 2-pass differential interferometry but it can, if available, be used to improve the simulated topographic phase.

The processing sequence consists of the following steps:

Step	**Program(s) used**
1. Interferometric processing	***create_offset, init_offset_orbit, init_offset, offset_pwr, offset_fit, SLC_interp, SLC_intf, base_init, adf, PHASE UNWRAPPING,***
2. Geocoding lookup table derivation	***create_dem_par, gc_map, geocode, create_diff_par, init_offsetm, offset_pwrm, offset_fitm, gc_map_fine, geocode***
3. Simulation of unwrapped topographic phase	***phase_sim***
4. LS-fit determination of phase scaling factors	***diff_ls_fit***
5. Subtraction of topographic phase	***diff_ls_unw***
6. Generation of displacement map	***adf, PHASE UNWRAPPING, dispmap***

For the processing we use the following pair of SLC images identified through the orbit numbers (ESA is acknowledged)

ERS-1 scene: 25394.slc (23 May 1996)
ERS-2 scene: 16242.slc (29 May 1998)

The images cover the area of Las Vegas, are 2500 pixels wide and 1800 pixels long. The following files are used in the processing example:

Filename	**Content**
25394.slc	SLC image (reference geometry)
25394.slc.par	SLC parameter file (reference geometry)
16242.slc	SLC image
16242.slc.par	SLC parameter file
25394.dem	DEM resampled to reference SAR geometry

The DEMO CD-ROM contains all the files.

Before processing, some preparation is required. First create a directory on the disk with the scene identifier. This can be the orbit number, the date of data acquisition, scene identifiers such as track and frame or any name other name you might want to select. In this example we use the combination of orbit numbers:

```
mkdir 25394_16242; cd 25394_16242
```

For the processing of an entire ERS interferogram the disk should have a minimum of 5 GB free space.

To start the files for the two SLCs and the DEM in radar geometry need to be copied to the working directory

A.1. Generation of the unwrapped interferogram

To generate the interferogram from which then the differential interferogram will be obtained, the standard processing as described in the User's Guide of the ISP module is used. Below the command and a brief explanation on what is done are provided.

Generation of ISP offset parameter file

```
create_offset 25394.slc.par 16242.slc.par 25394_16242.off 1
```

Initial estimate of offsets between SLC images using orbital information

```
init_offset_orbit 25394.slc.par 16242.slc.par 25394_16242.off
```

Refinement of initial estimates based on image intensity

```
init_offset 25394.slc 16242.slc 25394.slc.par 16242.slc.par 25394_16242.off
1 2
```

Offset estimation based on image intensity

```
offset_pwr 25394.slc 16242.slc 25394.slc.par 16242.slc.par 25394_16242.off
offs snr 64 64 offsets 1 32 32 7.0

offset_fit offs snr 25394_16242.off coffs coffsets 7.0 4 0
```

Co-registration of the two SLC images

```
SLC_interp 16242.slc 25394.slc.par 16242.slc.par 25394_16242.off 16242.rslc
16242.rslc.par
```

Generation of interferogram with 1x5 multi-look

```
SLC_intf 25394.slc 16242.rslc 25394.slc.par 16242.rslc.par 25394_16242.off
25394_16242.int 1 5 - - 1 1
```

Generation of multi-look SAR intensity image of reference SLC

```
multi_look 25394.slc 25394.slc.par 25394.mli 25394.mli.par 1 5
```

Computation of baseline file (perpendicular baseline information is saved to the file 25394_16242.base.perp)

```
base_init 25394.slc.par 16242.slc.par 25394_16242.off 25394_16242.int
25394_16242.base 0

base_perp 25394_16242.base 25394.slc.par 25394_16242.off >
25394_16242.base.perp
```

Adaptive filtering of interferogram. Running ***adf*** several times with a smaller coefficient and decreasing window size (e.g. 128, 64, 32) will lead to a better filtering but is time consuming.

```
adf 25394_16242.int 25394_16242.int_sm 25394_16242.smcc 2500 0.5 32 7 8 0 0
0.25
```

Phase unwrapping of interferogram. In this example we use the MCF algorithm.

```
rascc_mask 25394_16242.smcc 25394.mli 2500 1 1 0 1 1 0.3 0.0 - - - - -
25394_16242.mask.ras
```

```
mcf 25394_16242.int_sm 25394_16242.smcc 25394_16242.mask.ras
25394_16242.int_sm.unw 2500 1 9 18 - 1751 1 1 - 1200 1500
```

Areas of low coherence have been masked out. By using an interpolation the phase can be restored at these positions. For this it is referred to the User's Guide of the ISP module.

A.2. Generation of DEM in radar geometry

In order to calculate the topographic phase the DEM in radar geometry is needed. To obtain this first a lookup table linking the map geometry in which the DEM is provided and the radar geometry of the reference SAR image is needed. Then lookup table refinement needs to be performed. Therefore, the first steps of 2-pass differential interferometry are identical to GTC geocoding with a DEM in map coordinates.

Geocoding steps	**Program(s) used**
1.1. DEM parameter file creation	***create_dem_par***
1.2. Derivation of initial lookup table	***gc_map***
1.3. SAR intensity image simulation	***geocode***
1.4. Fine registration	***create_diff_par, init_offsetm, offset_pwrm, offset_fitm, gc_map_fine***
1.5. Forward geocoding from map to SAR coordinates	***geocode***

For detailed information it is referred to Example B on Geocoding with DEM in map coordinates in the DIFF&GEO User's Guide on Geocoding and Image Registration.

In this example the reference geometry is the one of the file 25394.mli. The resampled DEM is stored in the file 25394.dem. This file is available on the DEMO CD-ROM.

A.3. Simulation of unwrapped topographic phase

Once the interferogram (with curved Earth component) and the resampled heights in SAR geometry are available, differential interferometric processing can start.

The parameters of the reference SLC, the baseline model and the resampled DEM are used to simulate the unwrapped topographic phase. This is done with the program ***phase_sim*** as follows:

```
phase_sim 25394.slc.par 25394_16242.off 25394_16242.base 25394.dem
25394_16242.sim_unw 0 0
```

The program requires the baseline information which is stored in the file 25394_16242.base. In this example the perpendicular component of the baseline is 11 m.

A.4. LS-fit determination of phase scaling factors

The quality of the baseline used for the simulation of the unwrapped topographic phase is very important. Errors in the baseline model (occurring for example in the baseline estimation from orbit data) lead to a slight scaling of the topographic phase.

To generate a differential interferogram we need first to create a parameter file that will contain all parameter values describing the differential interferogram. To do this we use the program ***create_diff_par*** as follows

```
create_diff_par 25394_16242.off - 25394_16242.diff_par 0
```

This program generates the parameter file for the differential interferogram (similarly to the *.off file for the interferogram). The program is interactive.

Note that ***create_diff_par*** is used in two cases.

- For geocoding: the input file is the parameter file of the image to geocode
- For differential interferometry: the input file is the interferometric offset file

The program ***diff_ls_fit*** allows optimizing the phase scaling factors between the simulated and the real unwrapped phase image using a least squares fitting approach:

```
diff_ls_fit 25394_16242.int_sm.unw 25394_16242.sim_unw 25394_16242.diff_par
16 16 - lsfit.out
```

Notice that 25394_16242.int_sm.unw and 25394_16242.sim_unw correspond to the unwrapped phase of the original interferogram (without flat Earth phase trend removed). The phase scaling factors are written to the DIFF parameter file, 25394_16242.diff_par.

A.5. Subtraction of topographic phase

Then the differential phase image (using LS fit phase scaling factor) is generated with the program ***diff_ls_unw*** as follows:

```
diff_ls_unw 25394_16242.int_sm.unw 25394_16242.sim_unw 25394_16242.diff_par
25394_16242.diff.unw 0
```

with 25394_16242.diff.unw corresponding to the differential phase, i.e. the total interferometric phase minus the simulated topographic phase. The differential phase image is unwrapped (real valued data file). The differential phase image is in the SAR range-Doppler geometry.

The unwrapped differential phase can be visualized such as any other unwrapped phase image with the DISP program ***disrmg***:

```
disrmg 25394_16242.diff.unw 25394.mli 2500 1 1 0 1
```

and a SUNraster image file can be generated using:

```
rasrmg 25394_16242.diff.unw 25394.mli 2500 1 1 0 1 1 1. 1. .35 0.0 -1
25394_16242.diff.unw.ras
```

A.6. Generation of displacement map

To obtain a displacement map from the differential interferogram, further steps include the conversion to displacement and the geocoding.

The conversion to vertical displacements is done with the program ***dispmap***

```
dispmap 25394_16242.diff.unw 25394.dem 25394.slc.par 25394_16242.off
25394_16242.displ 1
```

To display the displacement file the program ***dishgt*** can be used as follows (2 cm per cycles are used):

```
dishgt 25394_16242.displ 25394.mli 2500 1 1 0 0.02
```

The displacement map 25394_16242.displ should include only motions of the ground. However, other factors like atmospheric effects, imperfect baseline estimation (and therefore flattening) and errors or inaccuracies in DEM affect the phase as well. From previous analysis with ERS SAR data over Las Vegas and from comparison with leveling data we concluded that the signal in the north of the city is due to subsidence (see Figure B.3 in Example B), but for the other signals there is no clear evidence of ground motion.

Geocoding of the displacement map (and of the interferograms) can be done with the program geocode_back as shown in the DIFF&GEO User's Guide on Geocoding and Image Registration.

B. 2-pass differential interferometric processing without phase unwrapping

For 2-pass differential interferometric approach a SAR image pair and a DEM (in map coordinates) are required. The 2-pass approach presented in this example does not require the unwrapped interferometric phase of the image pair (not the differential phase). As an advantage this makes the approach more robust in the sense, that it can be applied even if the interferometric phase could not be successfully unwrapped. As a draw back, on the other side, the scaling of the topographic phase cannot be improved with the LS-fitting approach.
The processing sequence consists of the following steps:

Step	**Program(s) used**
1. Interferometric processing	***create_offset, init_offset_orbit, init_offset, offset_pwr, offset_fit, SLC_interp, SLC_intf, base_init,***
2. Generation of DEM in radar geometry	***create_dem_par, gc_map, geocode, create_diff_par, init_offsetm, offset_pwrm, offset_fitm, gc_map_fine, geocode***
3. Simulation of unwrapped topographic phase	***phase_sim***
4. Subtraction of topographic phase	***create_diff_par, sub_phase***
5. Removal of linear phase trends	***base_est_fft, ph_slope_base*** (of ISP)
6. Generation of displacement map	***adf, PHASE UNWRAPPING, dispmap***

For the processing we use the following pair of SLC images identified through the orbit numbers (ESA is acknowledged)

ERS-1 scene: 25394.slc (23 May 1996)
ERS-2 scene: 16242.slc (29 May 1998)

The images cover the area of Las Vegas, are 2500 pixels wide and 1800 pixels long. The following files are used in the processing example:

Filename	**Content**
25394.slc	SLC image (reference geometry)
25394.slc.par	SLC parameter file (reference geometry)
16242.slc	SLC image
16242.slc.par	SLC parameter file
25394.dem	DEM resampled to reference SAR geometry

The DEMO CD-ROM contains all the files as well as a script to automatically process this differential interferogram starting from the two SLC images and the DEM resampled to slant range geometry (run_DIFF2_LasVegas). The CD-ROM also contains the list of commands in case the script cannot be run (com_DIFF2_LasVegas).

The script should be considered as an introduction to scripting and can be used for developing own scripts based on the user's particular needs. If the script is used for processing, it is strongly recommended to adapt it by selecting the programs actually needed for processing and by critically choosing the values of the parameters required by each individual program. For this purpose it is highly recommended to refer to the Reference Guide.

Before processing, some preparation is required. First create a directory on the disk with the scene identifier. This can be the orbit number, the date of data acquisition, scene identifiers such as track and frame or any name other name you might want to select. In this example we use the combination of orbit numbers:

```
mkdir 25394_16242; cd 25394_16242
```

To start the files for the two SLCs and the DEM in radar geometry need to be copied to the working directory

These preparation steps are not needed in case the script is run. The script will generate the directories, copy all needed files and run through the commands presented below.

For the processing of an entire ERS interferogram the disk should have a minimum of 5 GB free space.

B.1. Generation of the interferogram

To generate the interferogram from which then the differential interferogram will be obtained, the standard processing as described in the User's Guide of the ISP module is used. Below the command and a brief explanation on what is done are provided.

Generation of ISP offset parameter file

```
create_offset 25394.slc.par 16242.slc.par 25394_16242.off 1
```

Initial estimate of offsets between SLC images using orbital information

```
init_offset_orbit 25394.slc.par 16242.slc.par 25394_16242.off
```

Refinement of initial estimates based on image intensity

```
init_offset 25394.slc 16242.slc 25394.slc.par 16242.slc.par 25394_16242.off
1 2
```

Offset estimation based on image intensity

```
offset_pwr 25394.slc 16242.slc 25394.slc.par 16242.slc.par 25394_16242.off
offs snr 64 64 offsets 1 32 32 7.0
```

```
offset_fit offs snr 25394_16242.off coffs coffsets 7.0 4 0
```

Co-registration of the two SLC images

```
SLC_interp 16242.slc 25394.slc.par 16242.slc.par 25394_16242.off 16242.rslc
16242.rslc.par
```

Generation of interferogram with multi-look factors 1x5

```
SLC_intf 25394.slc 16242.rslc 25394.slc.par 16242.rslc.par 25394_16242.off
25394_16242.int 1 5 - - 1 1
```

Generation of multi-look SAR intensity image of reference SLC

```
multi_look 25394.slc 25394.slc.par 25394.mli 25394.mli.par 1 5
```

Computation of baseline file (perpendicular baseline information is saved to the file 25394_16242.base.perp)

```
base_init 25394.slc.par 16242.slc.par 25394_16242.off 25394_16242.int
25394_16242.base 0
```

```
base_perp 25394_16242.base 25394.slc.par 25394_16242.off >
25394_16242.base.perp
```

B.2. Generation of DEM in radar geometry

In order to calculate the topographic phase the DEM in radar geometry is needed. To obtain this first a lookup table linking the map geometry in which the DEM is provided and the radar geometry of the reference SAR image is needed. Then lookup table refinement needs to be performed. Therefore, the first steps of 2-pass differential interferometry are identical to GTC geocoding with a DEM in map coordinates.

Geocoding steps	**Program(s) used**
1.1. DEM parameter file creation	***create_dem_par***
1.2. Derivation of initial lookup table	***gc_map***
1.3. SAR intensity image simulation	***geocode***
1.4. Fine registration	***create_diff_par, init_offsetm, offset_pwrm, offset_fitm, gc_map_fine***
1.5. Forward geocoding from map to SAR coordinates	***geocode***

For detailed information it is referred to Example B on Geocoding with DEM in map coordinates in the DIFF&GEO User’s Guide on Geocoding and Image Registration.

In this example the reference geometry is the one of the file 25394.mli. The resampled DEM is stored in the file 25394.dem. This file is available on the DEMO CD-ROM.

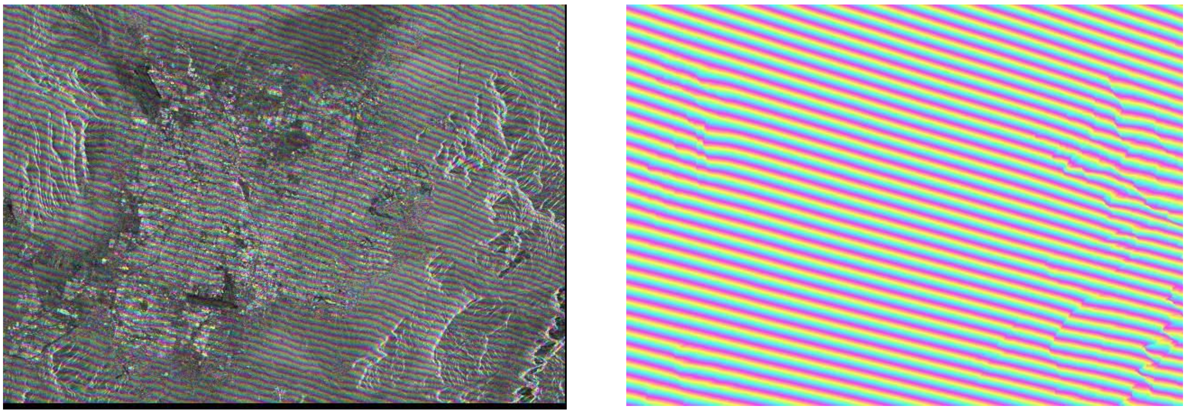
B.3. Simulation of unwrapped topographic phase

Once the interferogram (with curved Earth component) and the resampled heights in SAR geometry are available, differential interferometric processing can start.

The parameters of the reference SLC, the baseline model and the resampled DEM are used to simulate the unwrapped topographic phase. This is done with the program ***phase_sim*** as follows:

```
phase_sim 25394.slc.par 25394_16242.off 25394_16242.base 25394.dem
25394_16242.sim_unw 0 0
```

The program requires the baseline information which is stored in the file 25394_16242.base. In this example the perpendicular component of the baseline is 11 m. Figure B.1 shows the wrapped interferogram *.int with the SAR intensity in the background (obtained with ***rasmph_pwr*** or displayed with ***dismph_pwr***) and the corresponding simulated unwrapped unflattened phase. This can be displayed with ***disrmg*** or saved to file with ***rasrmg***. Because of the very short baseline, we have predominantly curved Earth fringes. The obliqueness of the fringes is related to the non-perfectly parallel orbits flown by the satellites at the two acquisitions.



(a) (b)

Figure B.1. Wrapped interferogram (a) and simulated interferometric phase (b).

B.4. Subtraction of topographic phase

The scaling of the unwrapped topographic phase is based on the existing baseline model. Linear residual phase trends resulting from errors in the baseline model (occurring for example in the baseline estimation from orbit data) may be removed later on by flattening the differential interferogram.

To generate a differential interferogram we need first to create a parameter file that will contain all parameter values describing the differential interferogram. To do this we use the program ***create_diff_par*** as follows

```
create_diff_par 25394_16242.off - 25394_16242.diff_par 0
```

This program generates the parameter file for the differential interferogram (similarly to the *.off file for the interferogram). The program is interactive.

Note that ***create_diff_par*** is used in two cases.

- For geocoding: the input file is the parameter file of the image to geocode
- For differential interferometry: the input file is the interferometric offset file

The complex valued differential interferogram, 25394_16242.diff_int is generated by subtracting the simulated unwrapped phase from the complex interferogram (both not flattened for the flat Earth phase trend). This is done with the program ***sub_phase*** as follows:

```
sub_phase    25394_16242.int    25394_16242.sim_unw    25394_16242.diff_par
25394_16242.diff_int 1
```

The argument of 25394_16242.diff_int corresponds to the wrapped differential interferometric phase, the magnitude of 25394_16242.diff_int is equal to the magnitude of 25394_16242.int, corresponding to the degree of coherence of the interferogram. 25394_16242.diff_int is in the SAR image geometry.

It shall be noticed that the differential interferogram could have been generated with the program ***SLC_diff_intf*** as well. In this case the original interferogram would have not been needed.

The differential interferogram can be displayed with the DISP programs ***dismph*** or ***dismph_pwr*** (or saved to SUNraster or bmp file with ***rasmph*** or ***rasmph_pwr***) as follows

```
dismph_pwr 25394_16242.diff_int 25394.mli 2500
```

Figure B.2 shows the wrapped differential interferometric phase overlaid on the SAR intensity image.

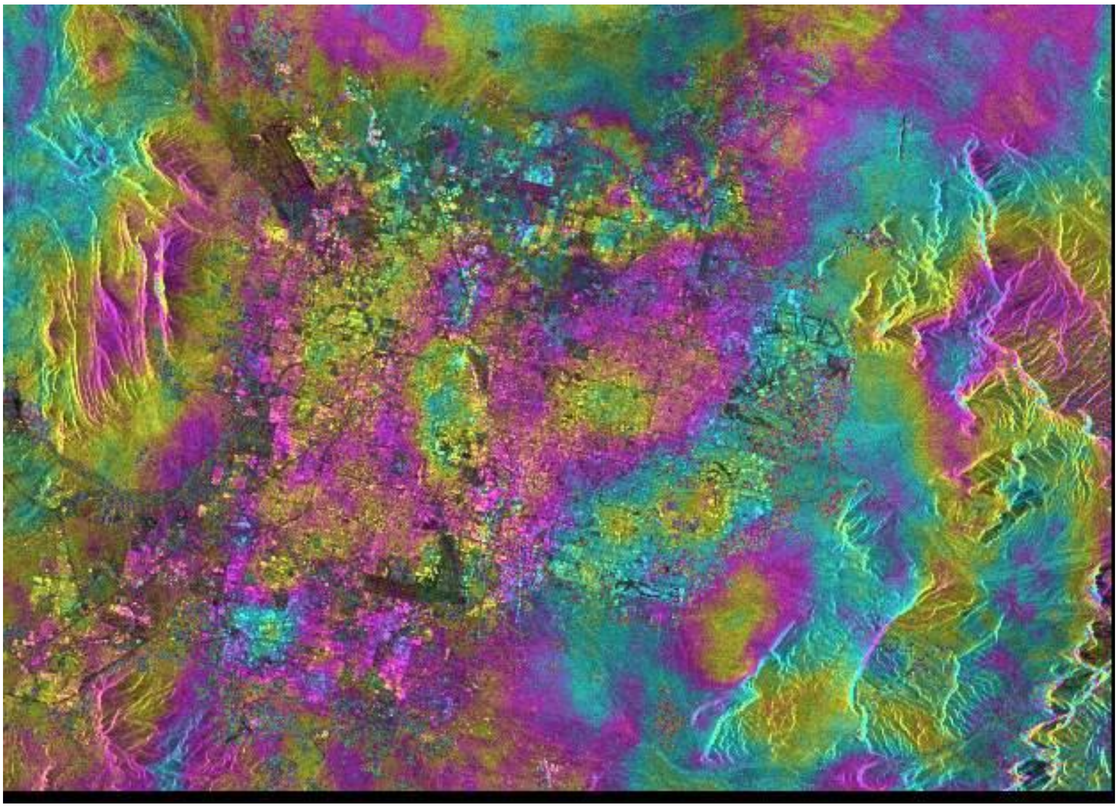


Figure B.2. Fringes of interferometric differential phase overlaid on the SAR intensity.

B.5. Removal of linear phase trends

Due to small errors in the baseline model the differential interferogram may exhibit a few fringes across the image. This is not the case in our example, however the processing steps are here illustrated for completeness.

The refinement process consists of
1) Estimation of residual baseline from the fringe rate
2) Correction of baseline with the estimate of the residual baseline
3) Simulation of phase with the new baseline values
4) Subtraction of new phase from original interferogram → new differential interferogram

To correct the baseline we first determine the residual baseline and then add it to the initial baseline estimate. This is estimated using the fringe rate of the differential interferogram. This is done with one of the programs of the ISP module ***base_init*** of ***base_est_fft***. In this example we use the program ***base_init*** specifying that range and azimuth FFTs are used to obtain the estimate of the residual baseline.

```
base_init 25394.slc.par 16242.slc.par 25394_16242.off 25394_16242.diff 25394_16242.base_res 4
```

To obtain an improved estimated of the baseline, the estimate of the residual baseline is then added to the initial baseline. To do this we use the program ***base_add*** as follows:

```
base_add 25394_16242.base 25394_16242.base_res 25394_16242.base1 1
```

At this stage the program ***phase_sim*** is used again to generate an unwrapped phase with the new baseline values

```
phase_sim 25394.slc.par 25394_16242.off 25394_16242.base1 25394.dem 25394_16242.sim_unw1 0 0 - -
```

The old and the new simulated phases can be compared with the DISP program ***dis2rmg***:

```
dis2rmg 25394_16242.sim_unw 25394_16242.sim_unw1 2500 2500
```

To subtract the new simulated unwrapped phase from the original interferogram in order to obtain a new differential interferogram the program ***sub_phase*** is used again:

```
sub_phase 25394_16242.int 25394_16242.sim_unw1 25394_16242.diff_par 25394_16242.diff_int1 1 0
```

The original and the new differential interferograms can be displayed with the DISP program ***dis2mph*** as follows:

```
dis2mph 25394_16242.diff_int 25394_16242.diff_int1 2500 2500
```

B.6. Generation of displacement map

To obtain a displacement map from the differential interferogram, further steps include the filtering, the phase unwrapping, the conversion to displacement and the geocoding. In this Section the commands are briefly illustrated. For details on individual program it is referred to the Reference Manual and to the User’s Guide of the ISP module.

Adaptive filtering of differential interferogram. Running ***adf*** several times with a smaller coefficient and decreasing window size (e.g. 128, 64, 32) will lead to a better filtering but is time consuming.

```
adf 25394_16242.diff_int 25394_16242.diff_int_sm 25394_16242.smcc 2500 0.7 32 7 8 0 0 0.25
```

```
dismph_pwr 25394_16242.diff_int_sm 2500
```

Phase unwrapping using minimum cost flow method (with masking)

```
rascc_mask 25394_16242.smcc 25394.mli 2500 1 1 0 1 1 0.25 0.0 0.1 0.9 1.0
0.35 1 25394_16242.mask.ras

mcf 25394_16242.diff_int_sm 25394_16242.smcc 25394_16242.mask.ras
25394_16242.diff_int_sm.unw 2500 1 9 18 - 1751 2 2 - 1250 850 0

disrmg 25394_16242.diff_int_sm.unw 25394.mli 2500 1 1 0 1 1 .5 1. .35 0.0
```

Areas of low coherence have been masked out. By using an interpolation the phase can be restored at these positions. For this it is referred to the User's Guide of the ISP module.

Conversion to vertical displacement with the program ***dispmap***

```
dispmap 25394_16242.diff_int_sm.unw 25394.dem 25394.slc.par 25394_16242.off
25394_16242.displ 1
```

To display the displacement file the program ***dishgt*** can be used as follows:

```
dishgt 25394_16242.displ 25394.mli 2500 1 1 0 0.02
```

The displacement map 25394_16242.displ should include only motions of the ground. However, other factors like atmospheric effects, imperfect baseline estimation (and therefore flattening) and errors or inaccuracies in DEM affect the phase as well. From previous analysis with ERS SAR data over Las Vegas and from comparison with leveling data we concluded that the signal in the north of the city is due to subsidence (see Figure B.3), but for the other signals there is no clear evidence of ground motion.

Geocoding of the displacement map (and of the interferograms) can be done with the program ***geocode_back*** as shown in the DIFF&GEO User's Guide on Geocoding and Image Registration.

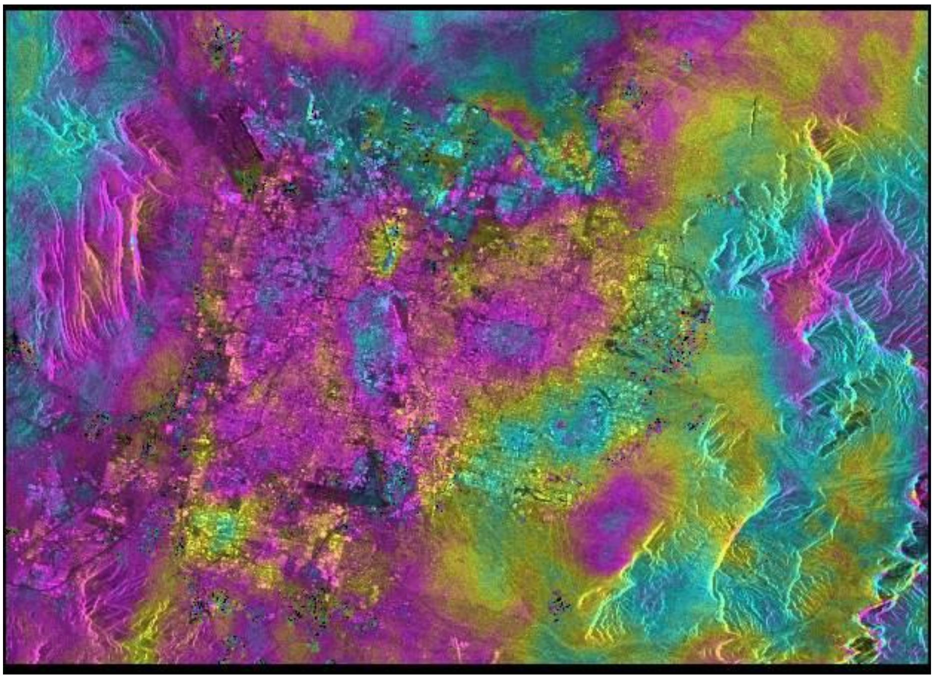


Figure B.3. Displacement map of the area of Las Vegas overlaid on the SAR intensity image. The only real displacement cone is the one visible in the upper part of the urban area. All other fringes should be related to atmospheric phase distortions.

C. 3-pass differential interferometric processing

For the 3-pass differential interferometric approach two SAR image pairs with the same reference geometry are used. This is the case if both pairs have the same reference slc (in this case a total of 3 slc are used, explaining the name of the approach), or, if the reference slc of the two pairs were registered to the same geometry prior to the interferometric processing. The difference between 3-pass and 4-pass differential interferometric processing is the additional registration step which is required in the 4-pass approach.

One of the pairs is used to estimate the topographic phase. As a consequence, this pair should optimally be acquired with a short acquisition time interval (to maximize the degree of coherence) and a rather large interferometric baseline (to increase the sensitivity of the interferometric phase to topography as compared to differential effects and heterogeneity in the atmospheric path delay). As this pair is used as reference to estimated the topographic phase it should not include the coherent displacement to be investigated.

The other pair has to consist of one image before and one after the coherent displacement. To optimize the sensitivity to the differential effects the baseline should be as small as possible. In the selection of the acquisition time interval the decreasing of the degree of coherence with time and the history of the investigated coherent displacement have to be considered.
The 3-pass approach presented in this example requires successful phase unwrapping of both interferograms. This is not an absolute requirement for 3-pass differential interferometry (see Example E) but it can, if available, be used to improve the scaling of the topographic phase.
For the processing we use the following three SLC images identified through the orbit numbers (ESA is acknowledged)

1) ERS-1 scene: 25394.slc (23 May 1996)
2) ERS-2 scene: 05721.slc (24 May 1996)
3) ERS-2 scene: 16242.slc (29 May 1998)

Scenes 1 and 2 (with 1-day repeat-pass) are used to generate the topographic phase information. For this reason we will refer to it as the “topographic” pair. The very short repeat-pass period should imply that no significant deformation occurred between the acquisitions. The perpendicular baseline of 108 m guarantees a good sensitivity of the interferometric phase to elevation.

Scenes 1 and 3 (with about 2 years temporal separation) are used to generate the differential interferogram since it contains a displacement occurred between the two image acquisitions. This pair will be referred to as the “differential” pair.

The “topographic” pair has already been processed to interferometry in the processing example of the ISP module. In this example however, the order of the images in the pair is reversed since image 25394.slc will be the reference for the common geometry. The “differential” pair has already been considered in the previous examples.

With respect to Examples A and B, here the source of the topographic fringes is another interferometric image instead of the DEM.

The images cover the area of Las Vegas, are 2500 pixels wide and 1800 pixels long. The following files are used in the processing example:

Filename	Content
25394.slc	SLC image (reference geometry) used for the topographic and the differential interferogram
25394.slc.par	SLC parameter file (reference geometry)
05721.slc	SLC image used for the topographic interferogram
05721.slc.par	SLC parameter file
16242.slc	SLC image used for the differential interferogram
16242.slc.par	SLC parameter file

The DEMO CD-ROM contains all the files as well as a script to automatically process this differential interferogram (run_DIFF3_LasVegas). The CD-ROM also contains the list of commands in case the script cannot be run (com_DIFF3_LasVegas).

The script should be considered as an introduction to scripting and can be used for developing own scripts based on the user's particular needs. If the script is used for processing, it is strongly recommended to adapt it by selecting the programs actually needed for processing and by critically choosing the values of the parameters required by each individual program. For this purpose it is highly recommended to refer to the Reference Guide.

Before processing, some preparation is required. First create two directories on the disk with the scene identifier. This can be the orbit number, the date of data acquisition, scene identifiers such as track and frame or any name other name you might want to select. The first directory will be used for the "topographic" processing, the second will be used for the "differential" processing. In this case the directories are named as follows:

```
mkdir 25394_05721; mkdir 25394_16242;
```

Make sure to copy the required files to the correct directories. The files 25394.slc and 25394.slc.par shall be copied to both directories.

These preparation steps are not needed in case the script is run. The script will generate the directories, copy all needed files and run through the commands automatically.

Processing of a full frame of ERS data requires about 10 GByte of disk space.

The processing will be structured as follows

1. Generation of topographic interferogram,
2. Generation of interferogram for the differential pair
3. Removal of topographic fringes to obtain the differential interferogram

The processing steps for points 1 and 2 have already been reported in the Example of the interferometric processing (see User's Guide of the ISP module). For this reason they are here only briefly described to let the reader focus on the processing sequence rather than on the single steps. More details are provided for the differential processing in point 3.

C.1. Topographic processing

The processing sequence to generate the topographic interferogram consists of the following steps.

Move to the directory where the processing has to take place

```
cd 25394_05721
```

Offset estimation of the SLC images

```
create_offset 25394.slc.par 05721.slc.par 25394_05721.off 1

init_offset_orbit 25394.slc.par 05721.slc.par 25394_05721.off

init_offset 25394.slc 05721.slc 25394.slc.par 05721.slc.par 25394_05721.off
1 2

offset_pwr 25394.slc 05721.slc 25394.slc.par 05721.slc.par 25394_05721.off
offs snr offsets

offset_fit offs snr 25394_05721.off coffs coffsets 0
```

SLC co-registration and computation of the interferogram with 1x5 multi-look factors

```
SLC_interp 05721.slc 25394.slc.par 05721.slc.par 25394_05721.off 05721.rslc
05721.rslc.par

SLC_intf 25394.slc 05721.rslc 25394.slc.par 05721.rslc.par 25394_05721.off
25394_05721.int 1 5 - - 1 1
```

Computation of the MLI intensity image of the SAR reference geometry SLC image

```
multi_look 25394.slc 25394.slc.par 25394.mli 25394.mli.par 1 5
```

Generation of baseline file (saving the perpendicular baseline model to file)

```
base_init 25394.slc.par 05721.slc.par 25394_05721.off 25394_05721.int
25394_05721.base 0

base_perp 25394_05721.base 25394.slc.par 25394_05721.off >
25394_05721.base.perp
```

Curved Earth phase trend removal ("flattening")

```
ph_slope_base 25394_05721.int 25394.slc.par 25394_05721.off
25394_05721.base 25394_05721.flt
```

Adaptive filtering of interferogram. Running ***adf*** several times with a smaller coefficient and decreasing window size (e.g. 128, 64, 32) will lead to a better filtering but is time consuming.

```
adf 25394_05721.flt 25394_05721.flt_sm 25394_05721.smcc 2500 .5 32 7 4
```

Phase unwrapping, in this example we use the branch-cut algorithm. The user can try using the MCF algorithm following the steps indicated in the ISP processing example or those shown in Example A. Make sure to adapt the file names and the parameter values to the this specific dataset.

```
corr_flag 25394_05721.smcc 25394_05721.flag 2500 0.3

residue 25394_05721.flt_sm 25394_05721.flag 2500

tree_cc 25394_05721.flag 2500
```

```
grasses 25394_05721.flt_sm 25394_05721.flag 25394_05721.flt_sm.unw 2500 - -
- - 1200 1500
```

Restoration of phase ramp to unwrapped phase

```
ph_slope_base 25394_05721.flt_sm.unw 25394.slc.par 25394_05721.off
25394_05721.base 25394_05721.int_sm.unw 0 1
```

The output of this processing is the unwrapped unflattened interferogram 25394_05721.int_sm.unw containing topographic phase and no displacement. The interferogram is in the geometry of the image 25394.

C.2. Generation of interferogram of differential pair

The processing sequence to generate the interferogram containing the differential phase consists of the following steps.

Move from the directory of topographic processing to the directory where the differential processing has to take place

```
cd ../25394_16242
```

Offset estimation between the two SLC images

```
create_offset 25394.slc.par 16242.slc.par 25394_16242.off 1

init_offset_orbit 25394.slc.par 16242.slc.par 25394_16242.off

init_offset 25394.slc 16242.slc 25394.slc.par 16242.slc.par 25394_16242.off
1 2

offset_pwr 25394.slc 16242.slc 25394.slc.par 16242.slc.par 25394_16242.off
offs snr 64 64 offsets 1 24 24 7.

offset_fit offs snr 25394_16242.off coffs coffsets 7.0 4 0
```

SLC co-registration and computation of the interferogram with 1x5 multi looks

```
SLC_interp 16242.slc 25394.slc.par 16242.slc.par 25394_16242.off 16242.rslc
16242.rslc.par

SLC_intf 25394.slc 16242.rslc 25394.slc.par 16242.rslc.par 25394_16242.off
25394_16242.int 1 5 - - 1 1
```

Generation of multi-look SAR intensity image of reference SLC image

```
multi_look 25394.slc 25394.slc.par 25394.mli 25394.mli.par 1 5
```

Generation of baseline file (perpendicular baseline is saved to file)

```
base_init 25394.slc.par 16242.slc.par 25394_16242.off 25394_16242.int
25394_16242.base 0

base_perp 25394_16242.base 25394.slc.par 25394_16242.off >
25394_16242.base.perp
```

Curved Earth phase trend removal ("flattening") and adaptive filtering of interferogram. Running ***adf*** several times with a smaller coefficient and decreasing window size (e.g. 128, 64, 32) will lead to a better filtering but is time consuming.

```
ph_slope_base 25394_16242.int 25394.slc.par 25394_16242.off 25394_16242.base 25394_16242.flt
```

```
adf 25394_16242.flt 25394_16242.flt_sm 25394_16242.smcc 2500 .5 32 7 4
```

Phase unwrapping, in this example we use the branch-cut algorithm. The user can try using the MCF algorithm following the steps indicated in the ISP processing example or those shown in Example A. Make sure to adapt the file names and the parameter values to the this specific dataset.

```
corr_flag 25394_16242.smcc 25394_16242.flag 2500 0.2
```

```
residue 25394_16242.flt_sm 25394_16242.flag 2500
```

```
tree_cc 25394_16242.flag 2500
```

```
grasses 25394_16242.flt_sm 25394_16242.flag 25394_16242.flt_sm.unw 2500 - - - - 1200 1500
```

Restoration of phase ramp to unwrapped phase

```
ph_slope_base 25394_16242.flt_sm.unw 25394.slc.par 25394_16242.off 25394_16242.base 25394_16242.int_sm.unw 0 1
```

The output of this processing is the unwrapped unflattened interferogram 25394_05721.int_sm.unw containing topographic phase and displacement. The interferogram is in the geometry of the image 25394.

C.3. 3-pass differential interferogram generation

Differential interferometric processing starts with the generation of the DIFF_par file with ***create_diff_par***. In this case since two interferograms are used, as input both ISP offset parameter files are used.

```
create_diff_par 25394_16242.off 25394_16242.off 25394_16242.diff_par
```

To generate the differential interferogram one could use the Least Squares offset fit with the combination of the programs ***diff_ls_fit / diff_ls_unw***. However in this case the method does not perform well on the image borders. The command lines are:

```
diff_ls_fit 25394_16242.int_sm.unw ../25394_05721/25394_05721.int_sm.unw 25394_16242.diff_par 32 32 -
```

```
diff_ls_unw 25394_16242.int_sm.unw ../25394_05721/25394_05721.int_sm.unw 25394_16242.diff_par 25394_16242.diff_unw 0
```

The other method consists in scaling the “topographic” pair according to baseline information and subtracting this phase from the “differential” pair. For this the programs ***scale_base*** and ***sub_phase*** are used as follows:

```
scale_base ../25394_05721/25394_05721.int_sm.unw 25394_16242.phase_sim 25394_16242.base 25394.slc.par 25394_16242.off ../25394_05721/25394_05721.base ../25394_05721/25394.slc.par ../25394_05721/25394_05721.off 0
```

```
sub_phase 25394_16242.int_sm.unw 25394_16242.phase_sim 25394_16242.diff_par 25394_16242.diff_unw 0
```

The file 25394_16242.diff_unw contains the unwrapped differential interferometric phase.

The unwrapped differential phase can be visualized such as any other unwrapped phase image with the DISP program ***disrmg***:

```
disrmg 25394_16242.diff_unw 25394.mli 2500 1 1 0 1
```

and a SUNraster image file can be generated using:

```
rasrmg 25394_16242.diff_unw 25394.mli 2500 1 1 0 1 1 1. 1. .35 0.0 -1 25394_16242.diff_unw.ras
```

C.4. Conversion of differential phase to displacement

To obtain from the unwrapped differential phase image the displacement map the program ***dispmap*** can be used:

```
dispmap 25394_16242.diff_unw - 25394.slc.par 25394_16242.off 25394_16242.displ 1 1.
```

To display the displacement file the program ***dishgt*** can be used as follows:

```
dishgt 25394_16242.displ 25394.mli 2500 1 1 0 0.02
```

The displacement map 25394_16242.displ should include only motions of the ground. However, other factors like atmospheric effects, imperfect baseline estimation (and therefore flattening) and errors or inaccuracies in DEM affect the phase as well. From previous analysis with ERS SAR data over Las Vegas and from comparison with leveling data we concluded that the signal in the north of the city is due to subsidence (see Figure C1), but for the other signals there is no clear evidence of ground motion.

Geocoding of the displacement map (and of the interferograms) can be done with the program geocode_back as shown in the DIFF&GEO User's Guide on Geocoding and Image Registration.

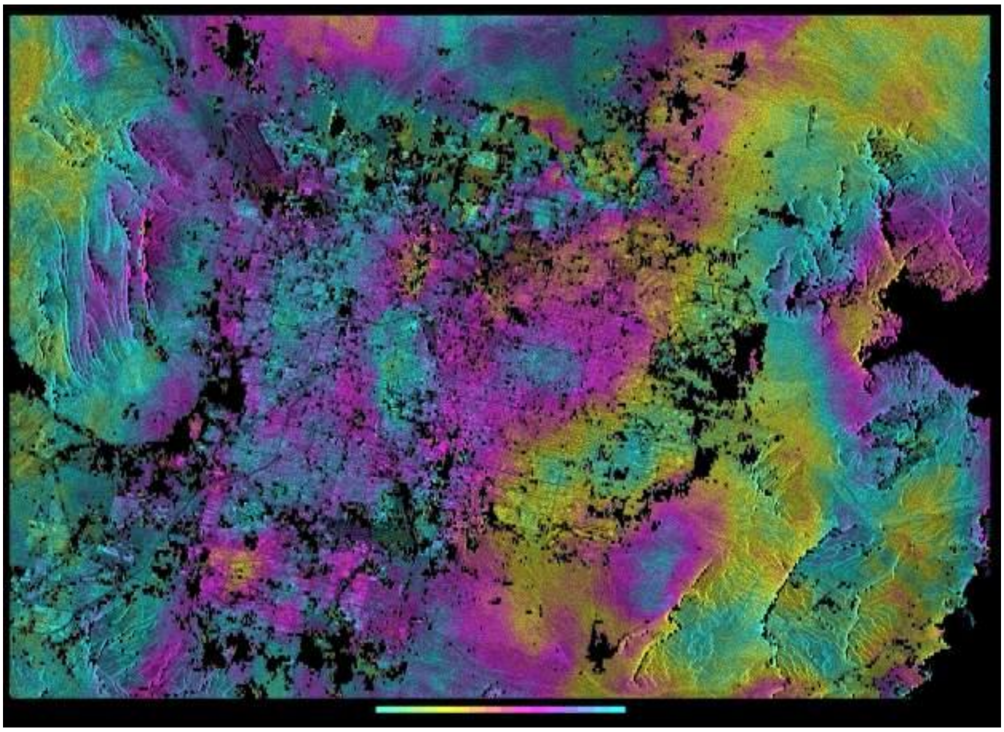


Figure C1. Displacement map of the area of Las Vegas overlaid on the SAR intensity image. The only real displacement cone is the one visible in the upper part of the urban area. All other fringes should be related to atmospheric phase distortions. Missing areas are due to low correlation in the interferogram used as topographic information.

D. 4-pass differential interferometric processing

For the 4-pass differential interferometric approach two independent SAR image pairs are required.

One of the pairs is used to estimate the topographic phase. As a consequence, this pair should optimally be acquired with a short acquisition time interval (to maximize the degree of coherence) and a rather large interferometric baseline (to increase the sensitivity of the interferometric phase to topography as compared to differential effects and heterogeneity in the atmospheric path delay). As this pair is used as reference to estimated the topographic phase it should not include the coherent displacement to be investigated.

The other pair has to consist of one image before and one after the coherent displacement. To optimize the sensitivity to the differential effects the baseline should be as small as possible. In the selection of the acquisition time interval the decreasing of the degree of coherence with time and the history of the investigated coherent displacement have to be considered.

The 4-pass approach presented in this example requires successful phase unwrapping of both interferograms. This is not an absolute requirement for 4-pass differential interferometry (see Example E), but it can, if available, be used to improve the scaling of the topographic phase.

For the processing we use the following three SLC images identified through the orbit numbers (ESA is acknowledged)

1) ERS-1 scene: 25394.slc (23 May 1996)
2) ERS-2 scene: 05721.slc (24 May 1996)
3) ERS-2 scene: 16242.slc (29 May 1998)

Scenes 2 and 1 (with 1-day repeat-pass) are used to generate the topographic phase information. For this reason we will refer to it as the “topographic” pair. The very short repeat-pass period should imply that no significant deformation occurred between the acquisitions. The perpendicular baseline of 108 m guarantees a good sensitivity of the interferometric phase to elevation.

Scenes 3 and 1 (with about 2 years temporal separation) are used to generate the differential interferogram since it contains a displacement occurred between the two image acquisitions. This pair will be referred to as the “differential” pair.

With respect to the 3-pass differential interferogram in Example C, we are now working with the same images but the reference images of the two interferograms are now different. In the case of the “topographic” pair the reference is image 05721.slc. In the case of the “differential” pair the reference is image 16242.slc.

With respect to Examples A and B, here the source of the topographic fringes is an interferometric image instead of the DEM.

The images cover the area of Las Vegas, are 2500 pixels wide and 1800 pixels long. The following files are used in the processing example:

Filename	Content
25394.slc	SLC image used for the topographic and the differential interferogram
25394.slc.par	SLC parameter file
05721.slc	SLC image (reference used for the topographic interferogram)
05721.slc.par	SLC parameter file
16242.slc	SLC image (reference used for the differential interferogram)
16242.slc.par	SLC parameter file

The DEMO CD-ROM contains all the files as well as a script to automatically process this differential interferogram (run_DIFF4_LasVegas). The CD-ROM also contains the list of commands in case the script cannot be run (com_DIFF4_LasVegas).

The script should be considered as an introduction to scripting and can be used for developing own scripts based on the user's particular needs. If the script is used for processing, it is strongly recommended to adapt it by selecting the programs actually needed for processing and by critically choosing the values of the parameters required by each individual program. For this purpose it is highly recommended to refer to the Reference Guide.

Before processing, some preparation is required. First create two directories on the disk with the scene identifier. This can be the orbit number, the date of data acquisition, scene identifiers such as track and frame or any name other name you might want to select. The first directory will be used for the "topographic" processing, the second will be used for the "differential" processing. In this case the directories are named as follows:

```
mkdir 05721_25394; mkdir 16242_25394;
```

Make sure to copy the required files to the correct directories. The files 25394.slc and 25394.slc.par shall be copied to both directories. These preparation steps are not needed in case the script is run. The script creates the directories, copies all needed files and runs through the commands presented below automatically.

Processing of a full frame of ERS data requires about 10 GByte of disk space.

The processing will be structured as follows
1. Generation of topographic interferogram,
2. Generation of interferogram for the differential pair
3. Co-registration of the two interferograms
4. Removal of topographic fringes to obtain the differential interferogram

The processing steps for points 1 and 2 have already been reported in the Example of the interferometric processing (see User's Guide of the ISP module). For this reason they are here only briefly described to let the reader focus on the processing sequence rather than on the single steps. More details are provided for the resampling of the two interferograms and the differential processing in points 3 and 4 respectively.

D.1. Topographic processing

The processing sequence to generate the topographic interferogram consists of the following steps. The processing steps are identical to those described in Section C.1, the difference here being that the images are reversed.

Move to the directory where the processing has to take place

```
cd 05721_25394
```

Offset estimation between the two SLC images

```
create_offset 05721.slc.par 25394.slc.par 05721_25394.off 1

init_offset_orbit 05721.slc.par 25394.slc.par 05721_25394.off

offset_pwr 05721.slc 25394.slc 05721.slc.par 25394.slc.par 05721_25394.off
offs snr 64 64 offsets 1 24 24 7.

offset_fit offs snr 05721_25394.off coffs coffsets 7.0 4 0
```

SLC co-registration and computation of the interferogram with 1x5 multi-looks

```
SLC_interp 25394.slc 05721.slc.par 25394.slc.par 05721_25394.off 25394.rslc
25394.rslc.par

SLC_intf 05721.slc 25394.rslc 05721.slc.par 25394.rslc.par 05721_25394.off
05721_25394.int 1 5 - - 1 1
```

Generation of multi-look intensity image for SAR reference image in the topographic interferogram

```
multi_look 05721.slc 05721.slc.par 05721.mli 05721.mli.par 1 5
```

Generation of baseline file (perpendicular component model values are saved to file)

```
base_orbit 05721.slc.par 25394.slc.par 05721_25394.base 0

base_perp 05721_25394.base 05721.slc.par 05721_25394.off >
05721_25394.base.perp
```

Curved Earth phase trend removal ("flattening") and adaptive filtering of interferogram. Running ***adf*** several times with a smaller coefficient and decreasing window size (e.g. 128, 64, 32) will lead to a better filtering but is time consuming.

```
ph_slope_base 05721_25394.int 05721.slc.par 05721_25394.off
05721_25394.base 05721_25394.flt

adf 05721_25394.flt 05721_25394.flt_sm 05721_25394.smcc 2500 .5 32 7 4
```

Phase unwrapping, in this example we use the branch-cut algorithm. The user can try using the MCF algorithm following the steps indicated in the ISP processing example or those shown in Example A. Make sure to adapt the file names and the parameter values to the this specific dataset.

```
corr_flag 05721_25394.smcc 05721_25394.flag 2500 0.3

residue 05721_25394.flt_sm 05721_25394.flag 2500

tree_cc 05721_25394.flag 2500
```

```
grasses 05721_25394.flt_sm 05721_25394.flag 05721_25394.flt_sm.unw 2500 - -
- - 1200 1500
```

Restoration of phase ramp to unwrapped phase

```
ph_slope_base 05721_25394.flt_sm.unw 05721.slc.par 05721_25394.off
05721_25394.base 05721_25394.int_sm.unw 0 1
```

The output of this processing is the unwrapped unflattened interferogram 05721_25394.int_sm.unw containing topographic phase and no displacement. The interferogram is in the geometry of the image 05721.

D.2. Generation of interferogram of differential pair

The processing sequence to generate the topographic interferogram consists of the following steps. The processing steps are identical to those described in Section C.2, the difference here being that the images are reversed.

Move from the topographic directory to the directory where the processing has to take place

```
cd ../16242_25394
```

Offset estimation between the two SLC images

```
create_offset 16242.slc.par 16242.slc.par 16242_25394.off 1

init_offset_orbit 16242.slc.par 25394.slc.par 16242_25394.off

offset_pwr 16242.slc 25394.slc 16242.slc.par 25394.slc.par 16242_25394.off
offs snr 64 64 offsets 1 24 24 7.

offset_fit offs snr 16242_25394.off coffs coffsets 7.0 4 0
```

SLC co-registration and computation of the interferogram with 1x5 multi-look images

```
SLC_interp 25394.slc 16242.slc.par 25394.slc.par 16242_25394.off 25394.rslc
25394.rslc.par

SLC_intf 16242.slc 25394.rslc 16242.slc.par 25394.rslc.par 16242_25394.off
16242_25394.int 1 5 - - 1 1
```

Generation of multi-look intensity image for SAR reference image in the differential interferogram

```
multi_look 16242.slc 16242.slc.par 16242.mli 16242.mli.par 1 5
```

Generation of baseline file

```
base_orbit 16242.slc.par 25394.slc.par 16242_25394.base
```

Curved Earth phase trend removal ("flattening") and adaptive filtering of interferogram. Running ***adf*** several times with a smaller coefficient and decreasing window size (e.g. 128, 64, 32) will lead to a better filtering but is time consuming.

```
ph_slope_base 16242_25394.int 16242.slc.par 16242_25394.off
16242_25394.base 16242_25394.flt
```

```
adf 16242_25394.flt 16242_25394.flt_sm 16242_25394.smcc 2500 .5 32 7 4
```

Phase unwrapping, in this example we use the branch-cut algorithm. The user can try using the MCF algorithm following the steps indicated in the ISP processing example or those shown in Example A. Make sure to adapt the file names and the parameter values to the this specific dataset.

```
corr_flag 16242_25394.smcc 16242_25394.flag 2500 0.4
```

```
residue 16242_25394.flt_sm 16242_25394.flag 2500
```

```
tree_cc 16242_25394.flag 2500
```

```
grasses 16242_25394.flt_sm 16242_25394.flag 16242_25394.flt_sm.unw 2500 - -
- - 1200 1500
```

Restoration of phase ramp to unwrapped phase

```
ph_slope_base 16242_25394.flt_sm.unw 25394.slc.par 16242_25394.off
16242_25394.base 16242_25394.int_sm.unw 0 1
```

The output of this processing is the unwrapped unflattened interferogram 16242_25394.int_sm.unw containing topographic phase and displacement. The interferogram is in the geometry of the image 16242.

D.3. Registration of the 2 interferograms to same (reference) geometry

Due to the different reference geometries of the differential pair and the topographic pair, the topographic pair image geometry needs first to be registered to the differential pair geometry (or vice versa). The registration requires the following steps:

Image registration steps	**Program(s) used**
1.1. DIFF parameter file creation	***create_diff_par***
1.2. Initial registration offset estimation	***init_offsetsm***
1.3. Detailed registration offsets estimation	***offset_pwrm***
1.4. Derivation of registration offset polynomials	***offset_fitm***
1.5. Transformation of topo-pair unwrapped phase to diff-pair reference geometry	***interp_real***

Move from the directory where the differential pair was processed to the upper level directory

```
cd ..
```

Generate a DIFF_par file for the co-registration with ***create_diff_par*** as follows

```
create_diff_par 05721_25394/05721_25394.off 16242_25394/16242_25394.off
diff_par
```

Compute the offsets between the geometries of the two interferograms using the correlation between the MLI intensity images. The sequence ***init_offsetm*** (initial estimate of offsets),

offset_pwrm (offset estimation), ***offset_fitm*** (generation of co-registration model) shall be used. In this example we consider the topographic pair as the reference geometry. The command line looks as follows:

```
init_offsetm 05721_25394/05721.mli 16242_25394/16242.mli diff_par 1 1

offset_pwrm 05721_25394/05721.mli 16242_25394/16242.mli diff_par offs snr
64 64 offsets 1 24 24 7.

offset_fitm offs snr diff_par coffs coffsets 7.0 4 0
```

At this stage the DIFF parameter file, diff_par, contains the registration polynomials.

With the offset polynomial available we can now resample any image in the differential pair geometry to the topographic pair geometry. In this case we want to resample (i) the flattened, unwrapped interferogram, (ii) the unflattened, unwrapped interferogram and (iii) the MLI intensity image. For all these image we can use the program ***interp_real*** since they are all real-valued. The command lines look as follow

```
interp_real 16242_25394/16242_25394.flt_sm.unw diff_par
16242_25394/16242_25394.flt_sm.unw.reg

interp_real 16242_25394/16242_25394.int_sm.unw diff_par
16242_25394/16242_25394.int_sm.unw.reg

interp_real 16242_25394/16242.mli diff_par 16242_25394/16242.mli.reg
```

The co-registered files have an extension .reg.

The nearest neighbor resampling is preferred because the unwrapped phase image may contain gaps (i.e. areas with the value equal to the NULL value 0.0).

D.4. 4-pass differential interferogram generation

Differential interferometric processing requires the DIFF_par that has been generated when resampling the interferograms to a common geometry.

To generate the differential interferogram one could use the Least Squares offset fit with the combination of the programs ***diff_ls_fit / diff_ls_unw***. However in this case the method does not perform well on the image borders. The command lines are:

```
diff_ls_fit 16242_25394/16242_25394.int_sm.unw.reg
05721_25394/05721_25394.int_sm.unw diff_par 32 32 -

diff_ls_unw 16242_25394/16242_25394.int_sm.unw.reg
05721_25394/05721_25394.int_sm.unw diff_par 16242_25394.diff_unw 0
```

The other method consists in scaling the “topographic” pair according to baseline information and subtracting this phase from the “differential” pair. For this the programs ***scale_base*** and ***sub_phase*** are used as follows:

```
scale_base 05721_25394/05721_25394.int_sm.unw
16242_25394/16242_25394.phase_sim 16242_25394/16242_25394.base
16242_25394/16242.slc.par 16242_25394/16242_25394.off
```

```
05721_25394/05721_25394.base                         05721_25394/05721.slc.par
05721_25394/05721_25394.off 0

sub_phase                             16242_25394/16242_25394.int_sm.unw.reg
16242_25394/16242_25394.phase_sim diff_par 16242_25394.diff_unw 0
```

The file 16242_25394.diff_unw contains the unwrapped differential interferometric phase. Compared to the images obtained in Examples A, B and C, here the order of the two images is reversed, which means that the deformation has changed sign.

The unwrapped differential phase can be visualized such as any other unwrapped phase image with the DISP program ***disrmg***:

```
disrmg 16242_25394.diff_unw 16242.mli 2500 1 1 0 1
```

and a SUNraster image file can be generated using:

```
rasrmg  16242_25394.diff_unw  16242.mli  2500  1  1  0  1  1  1.  1.  .35  0.0  -1
16242_25394.diff_unw.ras
```

D.5. Conversion of differential phase to displacement

To obtain from the unwrapped differential phase image the displacement map the program ***dispmap*** can be used:

```
dispmap      16242_25394.diff_unw          -      16242_25394/16242.slc.par
16242_25394/16242_25394.off 16242_25394.displ 1
```

To display the displacement file the program ***dishgt*** can be used as follows:

```
dishgt 16242_25394.displ 16242_25394/16242.mli 2500 1 1 0 0.02
```

The displacement map 16242_25394.displ should include only motions of the ground. However, other factors like atmospheric effects, imperfect baseline estimation (and therefore flattening) and errors or inaccuracies in DEM affect the phase as well. From previous analysis with ERS SAR data over Las Vegas and from comparison with leveling data we concluded that the signal in the north of the city is due to subsidence (see Figure D.1 in Example B), but for the other signals there is no clear evidence of ground motion.

Geocoding of the displacement map (and of the interferograms) can be done with the program ***geocode_back*** as shown in the DIFF&GEO User's Guide on Geocoding and Image Registration.

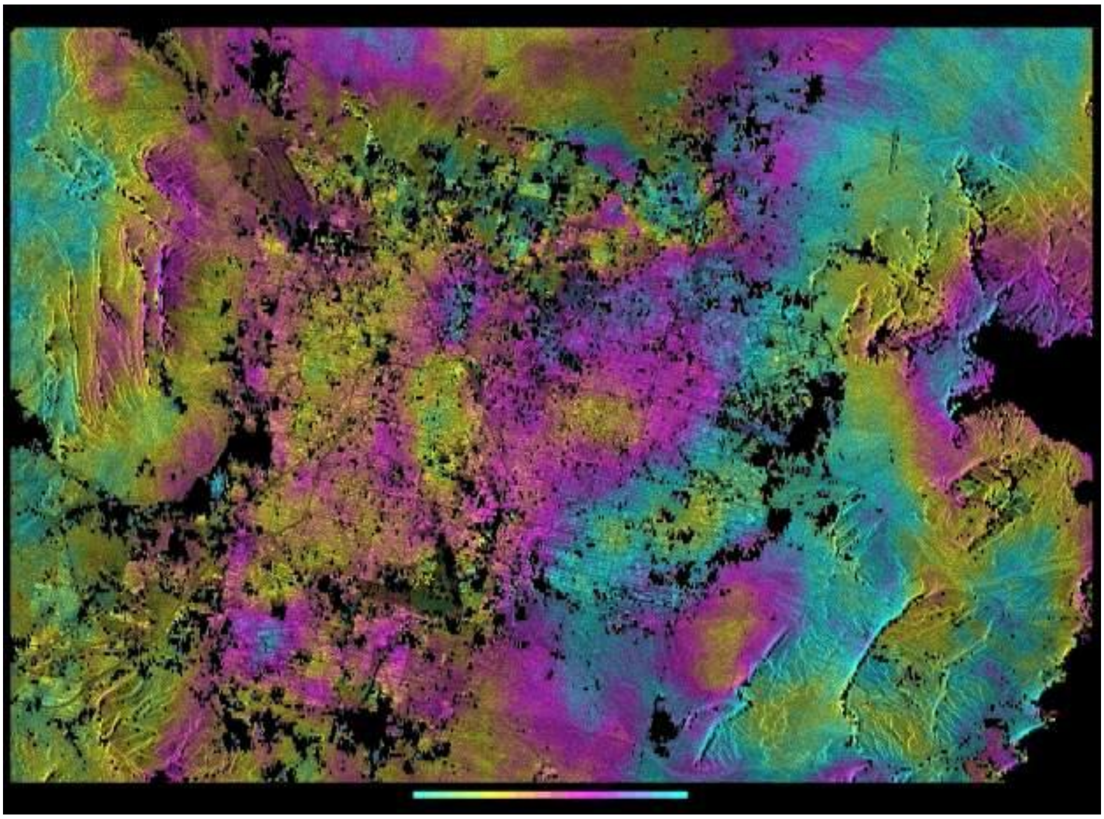


Figure D1. Displacement map of the area of Las Vegas overlaid on the SAR intensity image. The only real displacement cone is the one visible in the upper part of the urban area. All other fringes should be related to atmospheric phase distortions. Missing areas are due to low correlation in the interferogram used as topographic information.

E. Complex combination of interferograms

The complex combination of interferograms was included to increase the flexibility of the DIFF&GEO software. While the other approaches depend either on the availability of a DEM or on the successful unwrapping of the interferometric phase the complex combination of interferograms can be performed without meeting these requirements.

Once the two interferograms have been generated, the complex interferogram combination approach presented requires the following processing sequence:

Complex interferogram combination processing sequence	**Program(s) used**
1. Registration of the 2 interferograms to same (reference) geometry	***create_diff_par, init_offsetm, offset_pwrm, offset_fitm, interp_cpx***
2. Complex interferogram combination	***comb_interfs***
3. Removal of residual phase trend	***base_est_fft, ph_slope_base*** (part of ISP)

For the processing we use the following three SLC images identified through the orbit numbers (ESA is acknowledged)

1) ERS-1 scene: 25394.slc (23 May 1996)
2) ERS-2 scene: 05721.slc (24 May 1996)
3) ERS-2 scene: 16242.slc (29 May 1998)

Scenes 2 and 1 (with 1-day repeat-pass) are used to generate an interferogram that contains topographic phase information. We will refer to it as the “first” pair. The very short repeat-pass period should imply that no significant deformation occurred between the acquisitions. The perpendicular baseline of 108 m guarantees a good sensitivity of the interferometric phase to elevation.

Scenes 2 and 3 (with about 2 years temporal separation) are used to generate the differential interferogram since it contains a displacement occurred between the two image acquisitions. This pair will be referred to as the “second” pair.

With respect to the Examples C and D, we are now working with the same images but the reference images of the two interferograms are now the image 05721.

The images cover the area of Las Vegas, are 2500 pixels wide and 1800 pixels long. The following files are used in the processing example:

Filename	**Content**
25394.slc	SLC image used for the topographic and the differential interferogram
25394.slc.par	SLC parameter file
05721.slc	SLC image (reference used for the topographic interferogram)
05721.slc.par	SLC parameter file
16242.slc	SLC image (reference used for the differential interferogram)
16242.slc.par	SLC parameter file

The DEMO CD-ROM contains all the files as well as a script to automatically process this differential interferogram (run_DIFFCOMB_LasVegas). The CD-ROM also contains the list of commands in case the script cannot be run (com_DIFFCOMB_LasVegas).

The script should be considered as an introduction to scripting and can be used for developing own scripts based on the user's particular needs. If the script is used for processing, it is strongly recommended to adapt it by selecting the programs actually needed for processing and by critically choosing the values of the parameters required by each individual program. For this purpose it is highly recommended to refer to the Reference Guide.

Before processing, some preparation is required. First create two directories on the disk with the scene identifier. This can be the orbit number, the date of data acquisition, scene identifiers such as track and frame or any name other name you might want to select. The first directory will be used for the "topographic" processing, the second will be used for the "differential" processing. In this case the directories are named as follows:

```
mkdir 05721_25394; mkdir 05721_16242;
```

Make sure to copy the required files to the correct directories. The files 05721.slc and 05721.slc.par shall be copied to both directories.

These preparation steps are not needed in case the script is run. The script creates the directories, copies all needed files and runs through the commands presented below automatically.

Processing of a full frame of ERS data requires about 10 GByte of disk space.

The processing will be structured as follows
1. Generation of the first interferogram (wrapped)
2. Generation of the second interferogram (wrapped)
3. Co-registration of the two interferograms
4. Complex interferogram combination
5. Removal of residual phase trend

The processing steps for points 1 and 2 have already been reported in the Example of the interferometric processing (see User's Guide of the ISP module). For this reason they are here only briefly described to let the reader focus on the processing sequence rather than on the single steps. More details are provided for the resampling of the two interferograms, the complex combination and the removal of residual phase trends in points 3, 4 and 5 respectively.

E.1. Generation of first interferogram

The processing sequence to generate the first interferogram consists of the following steps. The processing steps are identical to those described in Section D.1, the difference here being that phase unwrapping is not applied.

Move to the directory where the processing has to take place

```
cd 05721_25394
```

Offset estimation between the two SLC images

```
create_offset 05721.slc.par 25394.slc.par 05721_25394.off 1

init_offset_orbit 05721.slc.par 25394.slc.par 05721_25394.off

offset_pwr 05721.slc 25394.slc 05721.slc.par 25394.slc.par 05721_25394.off
offs snr 64 64 offsets 1 24 24 7.

offset_fit offs snr 05721_25394.off coffs coffsets 7.0 4 0
```

SLC co-registration and computation of the interferogram

```
SLC_interp 25394.slc 05721.slc.par 25394.slc.par 05721_25394.off 25394.rslc
25394.rslc.par

SLC_intf 05721.slc 25394.rslc 05721.slc.par 25394.rslc.par 05721_25394.off
05721_25394.int 1 5 - - 1 1
```

Multi-look of SAR reference SLC image to obtain SAR intensity image

```
multi_look 05721.slc 05721.slc.par 05721.mli 05721.mli.par 1 5
```

Adaptive filtering of interferogram. Running ***adf*** several times with a smaller coefficient and decreasing window size (e.g. 128, 64, 32) will lead to a better filtering but is time consuming.

```
adf 05721_25394.int 05721_25394.int_sm  05721_25394.smcc 2500 .5 32 7 4
```

Generation of baseline file (the perpendicular baseline values are saved to file)

```
base_orbit 05721.slc.par 25394.slc.par 05721_25394.base 0

base_perp 05721_25394.base 05721.slc.par 05721_25394.off >
05721_25394.base.perp
```

Curved Earth phase trend removal ("flattening")

```
ph_slope_base 05721_25394.int_sm 05721.slc.par 05721_25394.off
05721_25394.base 05721_25394.flt_sm
```

The output of this processing is the (wrapped) flattened interferogram 05721_25394.flt_sm. The perpendicular component of the baseline is 106 m. The interferogram is in the geometry of the image 05721.

E.2. Generation of second interferogram

The processing sequence to generate the second interferogram is the same as described in Section D.1. It is here repeated for completeness.

Move from the directory where the first processing took place to the directory where the second processing has to take place

```
cd ../05721_16242
```

Offset estimation between the two SLCs

```
create_offset 05721.slc.par 16242.slc.par 05721_16242.off 1
```

```
init_offset_orbit 05721.slc.par 16242.slc.par 05721_16242.off
```

```
offset_pwr 05721.slc 16242.slc 05721.slc.par 16242.slc.par 05721_16242.off
offs snr 64 64 offsets 1 24 24 7.
```

```
offset_fit offs snr 05721_16242.off coffs coffsets 7.0 4 0
```

SLC co-registration and computation of the interferogram with 1x5 multi-look

```
SLC_interp 16242.slc 05721.slc.par 16242.slc.par 05721_16242.off 16242.rslc
16242.rslc.par
```

```
SLC_intf 05721.slc 16242.rslc 05721.slc.par 16242.rslc.par 05721_16242.off
05721_16242.int 1 5 - - 1 1
```

Generation of multi-look SAR intensity image from reference SLC image

```
multi_look 05721.slc 05721.slc.par 05721.mli 05721.mli.par 1 5
```

Adaptive filtering of interferogram. Running ***adf*** several times with a smaller coefficient and decreasing window size (e.g. 128, 64, 32) will lead to a better filtering but is time consuming.

```
adf 05721_16242.int 05721_16242.int_sm 05721_16242.smcc 2500 .5 32 7 4
```

Generation of baseline file (perpendicular component of the baseline is saved to file)

```
base_orbit 05721.slc.par 16242.slc.par 05721_16242.base 0
```

```
base_perp 05721_16242.base 05721.slc.par 05721_16242.off >
05721_16242.base.perp
```

Curved Earth phase trend removal ("flattening")

```
ph_slope_base 05721_16242.int_sm 05721.slc.par 05721_16242.off
05721_16242.base 05721_16242.flt_sm
```

The output of this processing is the (wrapped) flattened interferogram 05721_16242.flt_sm. The perpendicular baseline is 122 m. Also this interferogram is in the geometry of the image 05721.

E.3. Registration of the 2 interferograms to same (reference) geometry

If the reference image in the two interferograms had been different, co-registration offsets between the two geometries and resampling of the images in one geometry to the common reference must be applied before performing combination of the interferograms. The registration requires the following steps:

Image registration steps	Program(s) used
1.1. DIFF parameter file creation	***create_diff_par***
1.2. Initial registration offset estimation	***init_offsetsm***
1.3. Detailed registration offsets estimation	***offset_pwrm***
1.4. Derivation of registration offset polynomials	***offset_fitm***
1.5. Resampling of interferogram to reference geometry	***interp_cpx***

In this example this part is not required since the two interferograms have already a common reference geometry. In case the registration is required, it is referred to Section D.3 for command lines. It should be noticed that resampling of the interferogram is performed with the command ***interp_cpx*** since the interferogram is in complex format.

The nearest neighbor resampling is preferred over the interpolation approach because the unwrapped phase image may contain gaps (i.e. areas with the value equal to the NULL value 0.0).

E.4. Complex interferogram combination

With the complex valued interferogram of the two pairs in the same geometry the complex interferogram combination can be applied. This is done with the program ***comb_interfs***.

In this example we need first to move to the upper level directory

```
cd ..
```

and then use the following command line with factors 1 and -1

```
comb_interfs      05721_16242.int_sm      ../05721_25394/05721_25394.int_sm
05721_16242.base     ../05721_25394/05721_25394.base     1.     -1.     2500
05721_16242.diff_int_sm 05721_16242.base_comb 1.
```

The differential interferogram 05721_16242.diff_int_sm corresponds to an interferogram with (122-106) = 16 m perpendicular baseline and (735-1)=734 days time interval.

E.5. Removal of residual phase trend

Either the effective interferometric baseline, 05721_16242.base_comb, for the differential interferogram, 05721_16242.diff_int_sm, or a baseline determined using the program ***base_est_fft*** (of the ISP module) can be used to remove the remaining phase trend. The unflattened version of this interferogram can be obtained with the program ***ph_slope_base*** as follows

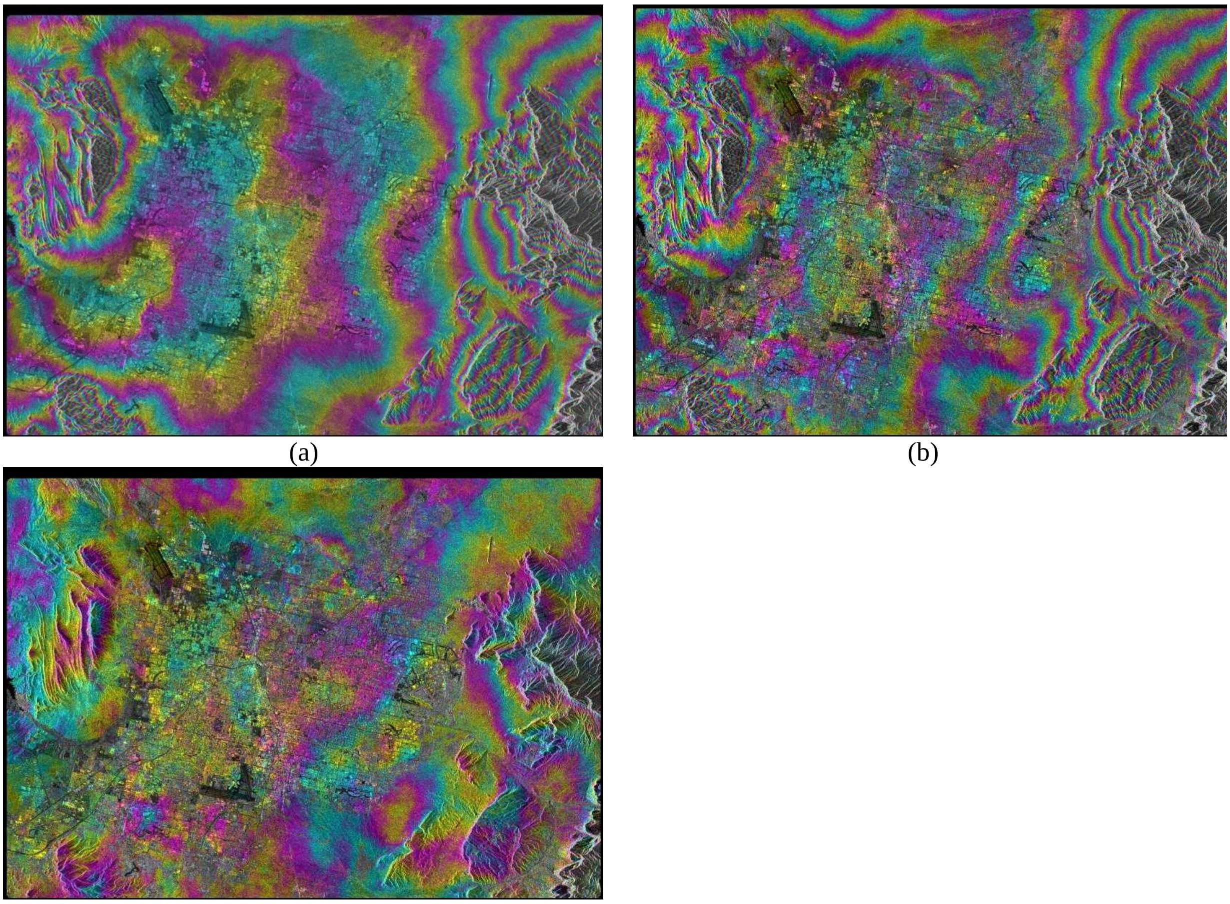
```
ph_slope_base    05721_16242.diff_int_sm    05721.slc.par    05721_16242.off
05721_16242.base_comb 05721_16242.diff_flt_sm
```

To display the complex interferogram overlaid on the reference SAR intensity image the DISP programs ***dismph_pwr*** can be used as follows

```
dismph_pwr 05721_16242.diff_flt_sm 05721.mli 2500
```

Figure E.1 illustrates the two original interferograms (flattened) and the resulting interferogram after complex combination. The combined interferogram shows clearly less fringes due to the smaller effective baseline. The results include motions of the ground (like in the north of Las Vegas), topography (in the east and west) and other factors affecting the phase like atmospheric effects and imperfect baseline estimation (and therefore flattening). The complex interferogram combination is to be used in the case of difficult phase unwrapping.

Notice that with the scaling of the wrapped phase the phase noise is also scaled. Therefore the approach is limited to small integer numbers. In order to reduce the up scaling of the phase noise filtering of the complex interferograms before complex interferogram combination is recommended.



(a) (b)

(c)

Figure E.1. Flattened interferogram of the 1-day image pair 05721-25394 with perpendicular baseline of 106 m (a), flattened interferogram of the 735-days image pair 05721-16242 with perpendicular baseline of 122 m (b), combined interferogram with effective perpendicular baseline of 16 m (c).