# GAMMA Interferometric Point Target Analysis Software (IPTA): Users Guide

## Contents

### User Handbook

# Introduction

The objective of the IPTA users guide is to give guideline to the use of the IPTA software package. The focus of the users guide is on the processing sequence. It tells the user what programs to use in a typical processing sequence without going into much detail on the functionality of the individual programs. A description of the functionality of the individual programs is provided in the IPTA reference manual.

There is not a single processing sequence for IPTA processing, and the software supports many options and quite different concepts. To keep the organization of the users guide simple it follows one important processing sequence, but alternatives and possible deviations are mentioned in many parts.

In the overview section the main steps of the IPTA processing are characterized. In the following sections these steps are discussed in more detail.

Graphs, plots and figures are used to illustrate how typical data sets may look.

# IPTA overview

In this section an overview on the main IPTA processing steps is given. These steps do not correspond to IPTA programs but to sections of the entire process. Typically, more than one program is required for such a step. Often, there is a selection between alternatives.

The phase model used for the IPTA is the same as used in conventional interferometry. The unwrapped interferometric phase is expressed as the sum of a topographic phase, a deformation phase, a differential path delay phase (also called atmospheric phase), and phase noise (or decorrelation) terms.

In the interferometric point target analysis the interferograms are only interpreted for the selected points. For efficiency and data storage reasons vector format data structures are used instead of the raster data format used in conventional interferometry. This permits a drastic reduction of the required disk space. For example, only 70 MB are used to keep track of 100,000 points in a stack of 70 SLCs. Similar point data stacks in vector format are used for interferograms, unwrapped phases, topographic heights, deformation rates, residual phases associated with the atmosphere and others. An additional data vector is used to save the point coordinates. Specific programs support the conversion between vector and raster data formats.

An important aspect of IPTA is that for point targets no spatial decorrelation occurs permitting interpretation of the interferometric phase of pairs with long baselines, even above the critical baseline. Obviously, a reflector must also remain stable over the time period of interest to permit analysis of the phase history. Based on these ideas one important objective of the IPTA is to achieve a more complete use of the available data. Through the use of point targets, interferometric pairs with long baselines can be used. Consequently, more observations are available permitting reduction of errors resulting from the atmospheric path delay and leading to better temporal coverage. Concerning the spatial coverage, there is the expectation that a few point targets may also be found in non-urban areas, permitting extension of the spatial coverage.

A flow chart of a typical IPTA processing sequence is shown in Figure 1.

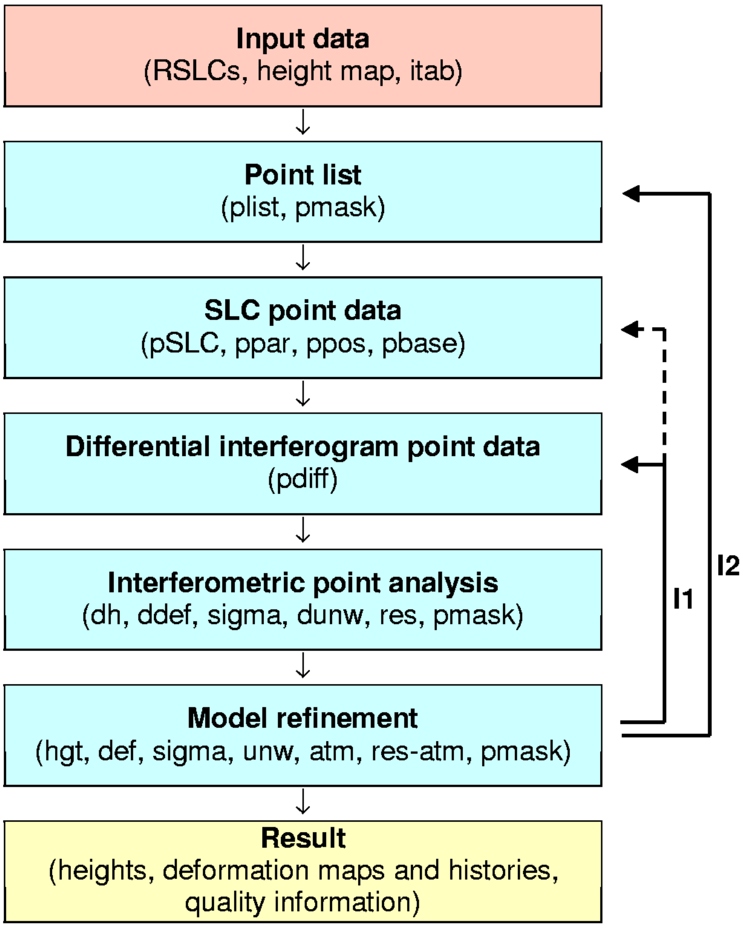


Figure 1: IPTA flow chart

The IPTA processing begins by assembling a stack of co-registered single look complex images (RSLCs) with the related SLC and orbit parameters and a text file (itab) that is used to specify which pairs shall be considered in the interferometric data stacks. Furthermore, a preliminary Digital Elevation Model (DEM) is used, if available.

Based on the registered SLCs, a candidate list of point targets (plist) is determined. Point targets do not show the speckle behavior associated with distributed targets since, by definition, a single coherent scatterer dominates the echo. The intensity and phase are directly dependent on the point target radar cross section and position. Consequently, criteria for an initial selection of point target candidates include low temporal variability of the backscattering coefficient. This works well for large data stacks. Alternative criteria, mainly of interest for small data stacks, are high backscattering and low spectral phase diversity. At this stage only “candidates” are selected. At a later stage of the processing the quality of the candidates will be more carefully evaluated. For each point of the plist a validity flag is kept in the mask list (pmask). The pmask permits to reject points of poor quality while keeping the plist and the related point data stacks unchanged.

For the candidate points the SLC values are extracted and written to a point data stack. For convenient access the related SLC parameter files are stored in a single binary file (ppar). Initial estimates of the interferometric baselines are calculated from the available orbit state vectors. All the baseline information is also stored in a single binary file (pbase).

Next, the differential interferograms are calculated. This is done by simulation of the unwrapped interferometric phase based on the currently available information, i.e. the initial baselines and the available DEM. Typically, no information on deformation and atmospheric phase delay is available at this stage. For each selected interferometric pair this simulation is calculated and subtracted from the interferogram. Depending on the accuracy of the assumed model parameters, the quality of the candidate points, and the baselines, these differential interferograms may look smooth or very noisy.

In the next step the stack of differential interferograms is analyzed. In the case of large enough stacks, this is done primarily in the temporal domain, i.e. across the layers of the stack. The phase model indicates a linear dependence of the topographic phase on the perpendicular baseline component. Thus, for the phase differences between two image points a linear dependence on the perpendicular baseline component is found, with the slope of the regression indicating the relative height correction. The phase standard deviation includes terms related to $\phi_{noise}$, $\phi_{atm}$, $\phi_{def}$, and baseline errors. Except for $\phi_{noise}$, these terms depend all on the distance between the two points. Consequently, for pairs with short spatial separation this regression analysis can be done independently of the quality of $\phi_{atm}$, $\phi_{def}$, and the baseline. The regression is further improved and made more robust by also considering linear phase dependence with time, equivalent to a constant deformation rate. One problem for the regression is that the phases in the differential interferograms are still wrapped. For large stacks performing a non-linear regression using the wrapped phase data is possible, but for small stacks, spatial phase unwrapping may be required prior to the regression step. The standard deviation of the phase from the regression is used as a quality measure, permitting to detect and reject points which are not suited for IPTA analysis. This regression analysis is performed for the entire point list.

The results from the regression analysis are height corrections, linear deformation rates, a quality measure, residual phases, and the unwrapped interferometric phase. These are used to improve the model. The height corrections, for example, are added to the DEM heights used in the simulation. The residual phase contains the atmospheric phase, which is related to the path delay heterogeneity at the two acquisition times of the pair, as well as non-linear deformation and error terms. Different phase terms can be discriminated based on their differing spatial and temporal dependencies. The atmospheric path delay is low-pass in the spatial dimension, but uncorrelated from pass to pass. The non-linear deformation is generally low-pass in the spatial and temporal dimension, but there may be cases where this is clearly not the case. Baseline related errors are low-pass in the spatial dimension and uncorrelated from pair to pair. Finally, the phase noise is random in both spatial and temporal dimensions.

An important aspect of the IPTA concept is the possibility of a step-wise, iterative improvement of different parameters. Main improvements include the consideration of a height correction, a deformation rate, a baseline refinement, atmospheric phase terms, and extension of the point list. The objective of the extension of the point list is to include as many points as possible. The evaluation of the quality of potential additional points can be done more reliably and efficiently if the improved model for the validated points is already available. This extension step also means that the first point target candidate selection can concentrate on candidates which are very likely to be point targets. Missing a fraction of the existing point targets is not severe at this stage as long as the selected points have a sufficient spatial coverage.

The IPTA result consists of the improved model, including heights, linear deformation rates, atmospheric phase delays, refined baselines, quality information, and non-linear deformation histories for each point.

---

# Input data

The three main inputs to the IPTA are:

- SLC data
- The IPTA "itab"
- A DEM if available

## SLC data:

The actual input to the IPTA are multiple co-registered SLCs and related auxiliary data (parameter files) in the formats used by the GAMMA ISP software.

Starting from SAR RAW data products the GAMMA Modular SAR Processor (MSP) is used to generate SLC images. Using the MSP has the advantage that the processing parameters may be optimized according to the specific needs. This may include special settings concerning the Doppler centroid, the deskewing, and focusing. Our current experience is that processing the SLC to the natural Doppler centroids (i.e. each scene to its own Doppler centroid) leads to good results. We recommend to process to deskewed (zero-Doppler) geometry to permit more accurate co-registration of the SLC. Very careful focusing is important (MSP program autof, possibly applied twice). An option might be to specifically set the spectral weighting functions so that point targets are optimally focused (MSP programs pre_rc and az_proc). Our current experience is that good results are also obtained with the default settings of these parameters.

The SLC data (from processing with MSP or as obtained from a processing facility / another SAR processor) are then co-registered. This process is supported by the GAMMA ISP. For this purpose one SLC image is selected as reference geometry. A natural choice is to select an SLC which is spatially and temporally near the center of the set of scenes. The objective of the selection is to optimize the robustness, automation, and above all, accuracy of the co-registration. The steps are (1) generation of an (ISP) offset parameter file, (2) initial offset estimation (from orbits and/or data), (3) precision offsets estimation, (4) least-squares registration polynomial estimation, and (5) resampling of SLC to reference geometry. For the precision offsets estimation the program offset_pwr which uses the intensity cross-correlation method is used. The coherence based method can be expected to fail for too large baselines due to geometric decorrelation. It is the important to achieve a very accurate co-registration (0.1 SLC pixel). In the SLC data resampling the use of adequate interpolators is important (as used in ISP program SLC_interp).

## The IPTA itab:

The IPTA itab is a Table in the form of an ASCII text file. In the "itab" the interferometric pairs which will be investigated are defined. For each pair it contains a line with the following information: 1) the reference SLC record number, 2) the second SLC record number, 3) the interferogram point data stack record number, and 4) a validity flag.

A typical IPTA itab used in the case of a large data stack looks as follows:

| | | | |
|---|---|---|---|
| 16 | 1 | 1 | 1 |
| 16 | 2 | 2 | 1 |
| 16 | 3 | 3 | 1 |
| . . . | . . . | . . . | . . . |
| 16 | 16 | 16 | 1 |
| . . . | . . . | . . . | . . . |
| 16 | 59 | 59 | 1 |

The same reference (SLC number 16) is used for all pairs. Consequently, for a stack of 59 SLC the itab will contains 59 lines. All flags are set to 1 (valid). Later on during the processing some flags may be changed to 0 for pairs which proof to be unreliable and which shall be excluded form the analysis.

A typical IPTA itab used in the case of a small data stack looks as follows:

| | | | |
|---|---|---|---|
| 1 | 2 | 1 | 1 |
| 1 | 3 | 2 | 1 |
| 1 | 4 | 3 | 1 |
| 1 | 5 | 4 | 1 |
| 1 | 6 | 5 | 1 |
| 2 | 3 | 6 | 1 |
| 2 | 4 | 7 | 1 |
| . . . | . . . | . . . | . . . |
| 5 | 6 | 15 | 1 |
| 1 | 1 | 16 | 1 |

Each possible pair is included. In addition, one auto-pair (1 – 1) is included. Consequently, for a stack of n SLC the itab will contains n*(n-1)/2 + 1 lines. During a first part of the processing all the pairs are considered. One option is then to only consider all pairs with one reference image in a second part of the processing. This is done by setting the validity flags accordingly.

For each line of the itab the interferometric data stacks will contain a record.

## Digital Elevation Model (DEM):

When available an external DEM should be used in support of the IPTA analysis. To have at least an approximate idea of the local terrain height makes the IPTA more robust and more efficient. In many cases control points extracted from the DEM may also serve as absolute height reference. Furthermore, the DEM can be used for terrain corrected geocoding.

To relate the correct height values to the selected points it is necessary to transform the DEM heights to the SAR geometry. This transformation needs to include a refinement step so that high positional accuracies are achieved. This is usually done using the procedure supported by the GAMMA DIFF&GEO Software.

# Point list generation

A key element of the IPTA is that the interferometric analysis is only done for selected points. The point list plays an essential role in this, as it contains the selected point definitions. Each point is defined by its range and azimuth coordinates. These coordinates are integer pixel numbers relative to the reference SLC geometry.

There are a variety of programs to generate and modify IPTA point lists.

One important case is that the points shall correspond to point targets. Point targets are of particular interest for their low geometric decorrelation which permits to include even interferometric pairs with baselines above the critical one in the analysis. There are programs included to identify point targets based on their special characteristics. This is done based on the registered SLCs.

It is also possible to define lists of points which are not point targets. In the case of short baselines good results have been generated using differential interferometry. The IPTA may be used as a toolbox to support the adequate combination of multiple interferometric observations. Related IPTA programs include mkgrid and image2pt.

Apart from the primary programs to define new point lists there are programs to modify and combine point lists.

Other important elements in the context of the point lists are the point mask and the point coordinates files. The point mask contains for each point of the list a validity flag. The masking concept permits to keep the point list unchanged but still to be able to exclude individual points from the investigation. The point coordinates file contains the real valued range and azimuth coordinates of point targets. For point targets the location can be determined with sub-pixel accuracy, which permits more accurate localization of the target. The experience with the data examples showed that good results are also achieved when using only the integer SLC pixel coordinates in the interferometric phase modeling. This is relevant as the sub-pixel determination of the point target location may not be very reliable for less dominating point targets.

### Generation of point target candidate list for large SLC data stacks:

Point targets do not show the speckle behavior associated with distributed targets since, by definition, a single coherent scatterer dominates the echo. One consequence is that a significantly lower temporal variability is observed for point targets as compared to distributed targets. This characteristic is used to identify point target candidates in large SLC data stacks (program pwr_stat). Pre-conditions for the use of this method are 1) well focused SLC data, 2) an accurate co-registration of the SLC and 3) an accurate radiometric calibration. As measure for the temporal variability the mean/sigma ratio (where mean is the temporal average of the backscattering and sigma is the standard deviation of the backscattering from this average) is used. For fully developed speckle a mean/sigma ratio of 1.0 is expected. Even smaller values can be observed if the variability is not just caused by speckle but also by temporal change. In the case of a stable point target a value significantly above 1.0 is expected. Candidates are selected by setting a lower threshold (e.g. 1.5) for the mean/sigma ratio.

As an additional criteria backscattering above an indicated threshold can be used (program pwr_stat). This criteria is related to the condition that the point target does not only need to be present, but it has to dominate the clutter scattering. The threshold is indicated by a factor to be multiplied with the spatial average of the backscattering. A factor 1.0 means that the backscattering has to be above the spatial average. This second condition permits to avoid selection of many point target candidates in low backscattering areas such as radar shadow.

The presence of point targets depends strongly on the scene. Many point targets are typically present in built-up areas. Very few point targets may be present in other areas.

The reliability of the point target candidate selection will depending on 1) the number of SLC in the stack, 2) the quality of the processing (focusing, registration, calibration), and 3) the thresholds applied. For a given case it is possible to generate candidate lists of different sizes, smaller and more reliable lists and larger but less reliable lists. At the beginning of an IPTA analysis it is recommended to work with a rather reliable list. It facilitates the initial iterations if a high percentage of the candidates are really point targets. Later on the completeness of the list will become important, which means that the objective is to generate a list which includes all point targets. At this stage it may be acceptable to also include many false alarms, i.e. points which will be again eliminated in the quality control.

The temporal variability criteria works well for large stacks (> 25 images). For smaller stacks it becomes less reliable. Therefore, other criteria are included in the IPTA for this case.

### Generation of point target candidate list for small SLC data stacks:

In the case of small SLC data stacks the temporal variability criteria to select point target candidates becomes unreliable for statistical reasons. Therefore, the use of another criteria is required.

Well focused, dominating point targets have characteristic spectral behavior which differs from that of distributed targets. The IPTA program sp_stat permits to identify point targets based on its low spectral phase diversity. This is done for a single SLC. As an additional dominant backscattering (i.e. backscattering above a threshold) is used.

Based on a single SLC a first point target candidate list is generated. This can be repeated for other SLC and the resulting point lists can be merged into a single list of increased reliability (program merge_pt).

As in the case of the large lists it is important to remember that at this stage only candidates are selected. At a later stage of the processing the quality of the candidates will be more carefully evaluated, respectively candidates of poor quality will be excluded.

---

# SLC point data

For the candidate points defined in a point list SLC values are extracted from the co-registered SLC and written to an SLC point data stack. This is done using one of the programs data2pt or xpt_slc. In the case of data2pt this is done by simply taking the SLC values at the selected pixels. In the case of xpt_slc the exact sub-pixel position of the point target location is determined. The SLC value is then extracted at this interpolated location, and the coordinate is written to the positions point data stack which contains for each point and SLC the real valued (sub-pixel) point position information.

Apart from the SLC data values the SLC parameter files are also organized in a stack for more convenient access in the IPTA. The program SLC_par_pt permits to read and write individual SLC parameter files from and to the SLC parameter file stack. Each record of this stack contains in binary format the contents of the SLC related parameter file. Record numbers need to be kept consistent with the SLC point data stack.

Based on the orbit state vectors available in the SLC parameter files, respectively in the SLC parameter file stack, initial estimates of the interferometric baselines are calculated using the program base_orbit_pt. The use of the most accurate orbit state vectors (as PRC or DELFT state vectors) as supported in the GAMMA software is recommended.

One aspect of the SLC point data generation is that the data volume is dramatically reduced in this step. While a single full frame SLC has a size of the order of 500 Mbyte the related point data is only a 4 Mbyte when assuming 1’000’000 points. In the case of a large stack of 60 SLC the reduction is from 30 Gbyte to 240 Mbyte.

---

# Differential interferogram point data

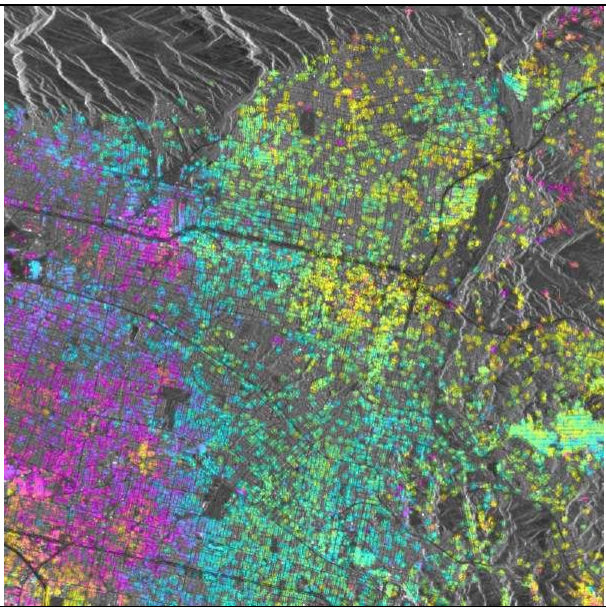
In the next step differential interferograms are calculated. The differential interferograms are calculated by subtracting simulated unwrapped phases from the complex valued interferograms. This is done for each interferometric pair defined in the itab and for each point defined in the point list.

The interferograms are calculated using the program intf_pt. The main inputs in the interferogram calculation are the SLC point data stack, the itab, and the point list.

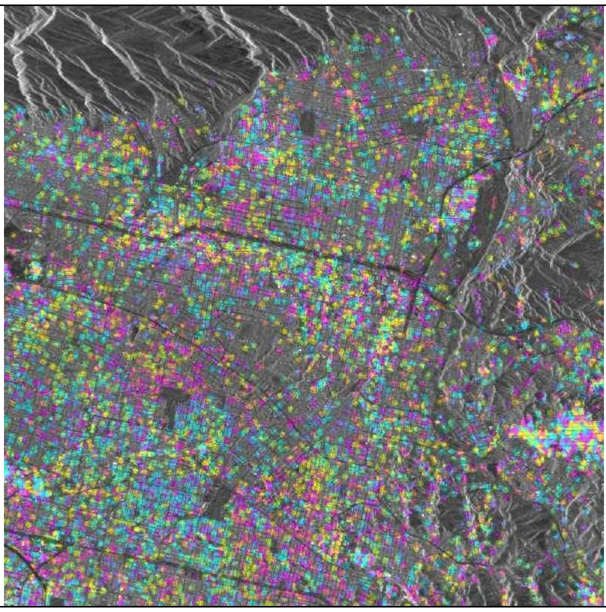
The unwrapped interferometric phase is estimated from the currently available knowledge on sensor (e.g. baseline), scene topography, linear deformation rates, and heterogeneity in the atmospheric path delay. The program phase_sim_pt supports the calculation of the interferometric phase including the effects of the scene topography and linear deformations. The phase model used is identical with what is considered in the DIFF&GEO software for conventional interferometric processing. For each selected interferometric pair this simulation is calculated and subtracted from the interferogram (using sub_phase_pt). Depending on the accuracy of the assumed model parameters, the quality of the candidate points, and parameters as the baseline, these differential interferograms may look smooth or very noisy.

For quality control and to decide on next steps it is important to visualize intermediate results of an IPTA project. To display records of point data stacks the related data is transformed to raster data. To make the information at the individual points better visible the point can be expanded to circle with a diameter of several pixels. The conversion between the IPTA vector and raster formats is supported by the programs data2pt, pt2d, and pt2data.

Below an example of two differential interferogram (i.e. two records of a point data record) as obtained in an initial processing run for a pair with a short baseline and one with a long baseline are shown.



ERS differential interferogram as obtained in an initial processing run for a pair number 23 with a short baseline (210 m) is shown. One color cycle corresponds to a 2PI phase cycle. The spatial smoothness of the phase indicates that the phase can be interpreted. Color, respectively phase changes are related to residual topography, deformation, atmospheric path delay heterogeneity, and baseline errors.



ERS differential interferogram as obtained in an initial processing run for a pair number 22 with a long baseline (-1179 m) is shown. Considering the high spatial phase noise it is not clear if the differential interferometric phase may be interpreted. At this large baseline the sensitivity of the interferometric phase to terrain height is very high. Even residual height errors of a few meters result a noisy appearance of the differential interferogram.

In an initial run the best available model typically only includes baselines estimated from the orbit data and heights extracted from an available DEM (respectively an assumed constant height if not available). Deformation information and information on the heterogeneity in the atmospheric path delay will only be available later in the analysis.

Spatial filtering of the differential interferograms is an option when the phase is almost constant over the filter window, except for phase noise. In the case of the initial differential interferogram with a large baseline shown above spatial filtering is not applicable. But later on when an improved model with updated heights will be used this will be an option.

---

# Interferometric point analysis

In the next step the stack of differential interferograms is analyzed. In an initial run the input provided is a point data stack of complex valued differential interferograms. In further runs or after application of spatial phase unwrapping the input may also be a point data stack of real valued unwrapped differential interferometric phases.

For pairs of points (a reference point and another point) the baseline and time dependence of the spatial difference in the differential interferometric phases are analyzed. For a stack of x records this means that x spatial differences between differential interferometric phases are considered.

The phase model indicates a linear dependence of the topographic phase on the perpendicular baseline component with the slope of the regression indicating the relative height correction. This height correction is the height which needs to be added to the second point, so that its phase becomes consistent with that of the reference point.

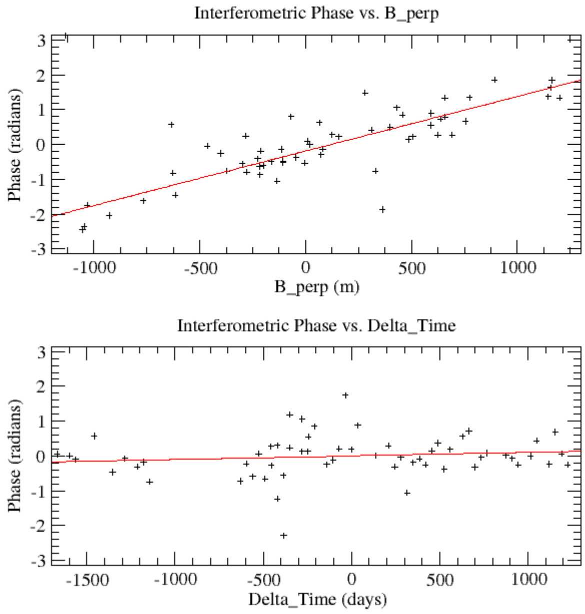
Furthermore, the phase model indicates a linear time dependence for deformation rates which differ between the second point and the reference point. So the regression is further improved and made more robust by also considering a linear phase dependence with time, which is equivalent to a constant relative deformation rate.

A two-dimensional regression analysis is done with the dimensions corresponding to the perpendicular baseline (of the interferometric pairs) and to the time difference (between the two SLC of the interferometric pairs). The related slopes correspond to relative terrain height corrections and relative linear deformation rates.

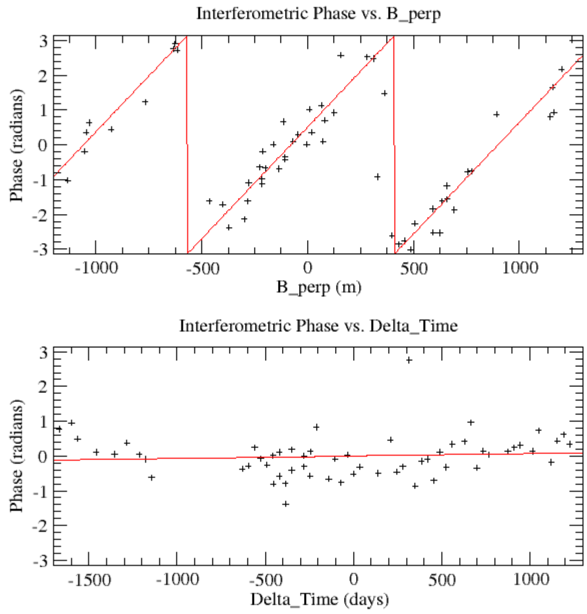
For complex valued differential interferograms one problem for the regression is that the phases are still wrapped. For large stacks performing a two dimensional linear regression using the wrapped phase data is possible. In this case one part of the optimization is to find the correct phase ambiguities. For small stacks spatial phase unwrapping may be required prior to the regression step. This is supported by the program mcf_pt using a phase unwrapping algorithm based on Minimum Cost Flow optimization techniques applied to a triangular irregular network.

The phase differences will of course not match perfectly with the two-dimensional regression. The phase standard deviation includes terms related to phase noise ($\phi_{noise}$), atmospheric path delay related phase ($\phi_{atm}$), deformation phase ($\phi_{def}$), and baseline error related phase. Except for $\phi_{noise}$, these terms depend all on the distance between the two points. Consequently, for pairs with short spatial separation this regression analysis can be done independently of the quality of $\phi_{atm}$, $\phi_{def}$, and the baseline. The standard deviation of the phase from the regression is used as a quality measure, permitting for example to detect and reject points which are not suited for IPTA analysis.

This regression analysis can either be done interactively, using the program dis_ipta, or automated using one of the programs multi_def_pt or def_mod_pt. The same methodology is also applied in the program qc_pt which is used to qualify the individual points. The central algorithm used in these programs is identical. What is different is to what point pairs it is applied. In dis_ipta it is applied to operator selected pairs, in def_mod_pt to all points of the point list with one reference point, and in multi_def_pt to all points of the point list with one global reference point and a patch-wise local reference point. In qc_pt the main objective is to determine the quality of each point for IPTA. The phase standard deviation from the regression is used as measure. But as this measure will depend not only on the second point but also on the reference point many possible local reference points are used to determine the quality of a point.




Two-dimensional phase regression plot for a case with a low relative height correction. In the upper plot the baseline dependence of the phase difference is shown after compensation of the time dependence and in the lower plot the time dependence after compensation of the baseline dependence.

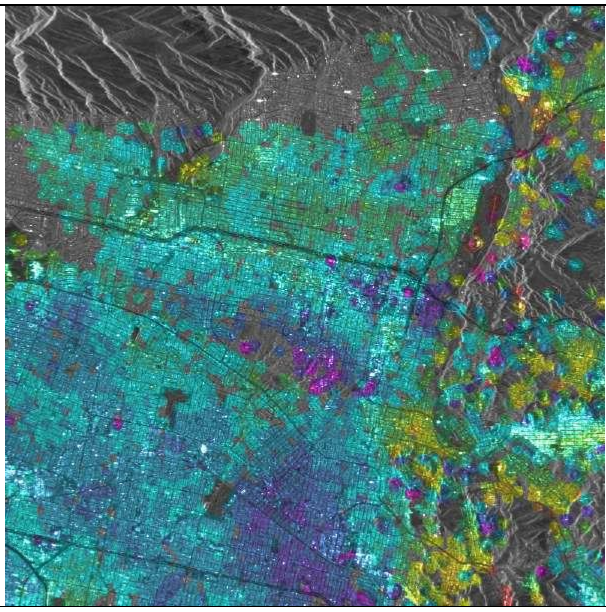



Two-dimensional phase regression plot for a case with a high relative height correction. Unwrapping of the phase differences was done successfully as part of the regression analysis. For the display the unwrapped phases were re-wrapped.

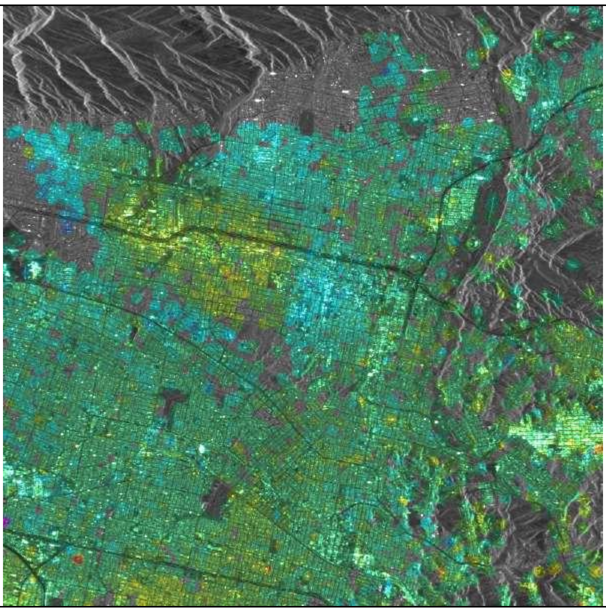
The results from the regression analysis include:

- height corrections,
- linear deformation rate corrections,
- point quality measures (phase standard deviation from regression fit),
- residual phases (deviation from regression fit) for each record of interferogram stack,
- unwrapped interferometric phase for each record of interferogram stack .

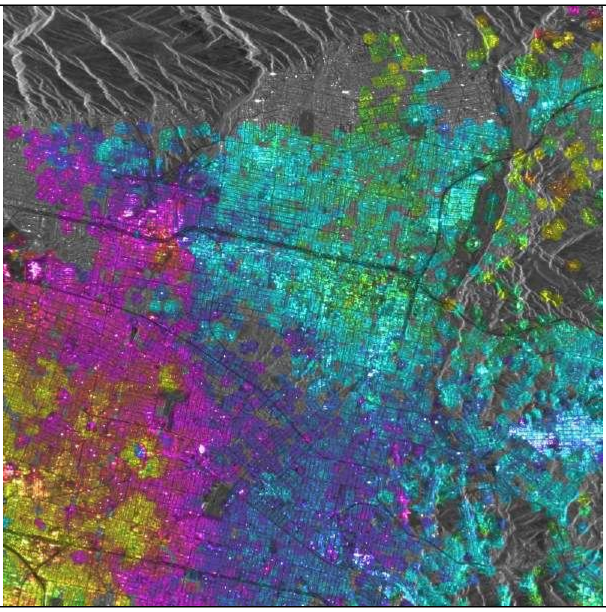
In the programs def_mot_pt and multi_def_pt non-zero values are only assigned to points with a quality above the indicated threshold. In the following an example for an output as obtained in an initial run of multi_def_pt on an ERS data stack of 59 SLC is shown.



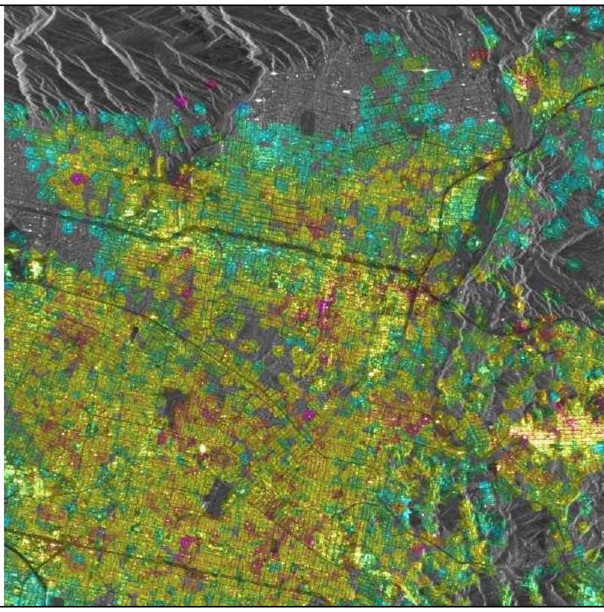
Height corrections derived using multi_def_pt on a stack of 59 ERS scenes. One color cycle indicates 100m relative height correction. Initial height reference is DEM at 90m resolution.



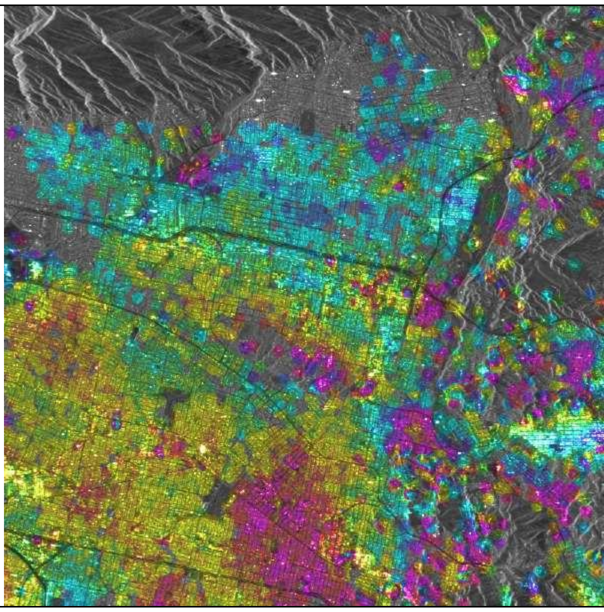
Relative linear deformation rate derived using multi_def_pt on a stack of 59 ERS scenes. One color cycle corresponds to 0.01 m/year relative linear deformation rate. No deformation was used as the initial deformation rate reference.



Residual phase of record 23 derived using multi_def_pt on a stack of 59 ERS scenes. One color cycle corresponds to 2PI of residual phase. The residual phase includes the heterogeneity in the atmospheric path delay as well as non-linear deformation and other terms.



Phase standard deviation from regression fit as calculated by multi_def_pt on a stack of 59 ERS scenes. One color cycle corresponds to 1.0 radian of phase standard deviation. In the multi-def_pt a phase standard deviation threshold of 1.0 was used in this case, points with higher noise were excluded.



Unwrapped differential interferometric phase for pair 22 with a large –1179 m baseline. One color cycle corresponds to 6PI.

These results are then used to improve the model.

# Model refinement

The results from the regression analysis are used to update the model.

## Heights:

The height corrections are added to the heights used in the simulation (program lin_comb_pt). For some points no height corrections were determined because the point is not suited or because the estimation of a height correction was not successful for other reasons. The two possibilities to maintain a valid height for such points are to keep the initial height without correction, or to spatially interpolate the reliable height corrections using the program expand_data_pt.

Concerning the height corrections it is important to remember that the heights correspond to the scatterer location (phase center) which may significantly deviate from the local terrain height. Some scatterers may be on top of buildings while others at ground level. This also introduces significant point to point differences in the interferometric heights. This should be kept in mind when filtering or interpolating point based interferometric heights.

## Linear deformation:

In the general case land surface deformation is non-linear in time. Nevertheless, very often the behavior is quite well described with a linear temporal development, respectively a constant deformation rate (also called linear deformation rate). As linear deformation we define the linear component (or first order approximation) of the deformation history.

The linear deformation rate corrections are added to the linear deformation rates used in the simulation (program lin_comb_pt). In an initial run no deformation is used in the simulation, so that the linear deformation rate corrections will correspond directly to the updated linear deformation rate. For some points no deformation rate corrections were determined because the point is not suited or because the estimation of a deformation rate correction was not successful for other reasons. The two possibilities to maintain a valid deformation rate for such points are to keep the initial value without correction, or to spatially interpolate the reliable linear deformation rate corrections using the program expand_data_pt.

In general the linear deformation rate is spatially well correlated. But as in the case of the height corrections there may be some point wise effects for example related to the expansion of structures with temperature.

In the context of filtering and interpolation it should be kept in mind that small scale deformation phenomena may be lost or reduced by spatial filtering.

## Point quality:

The point quality is not updated but re-calculated in each run. A high phase standard deviation may also be caused by a poor model. Especially for points which are far away from the reference point inaccuracies in the baselines, height model, deformation model, and atmospheric phase cause phase noise.

For non-successful regression fits the phase standard deviations are of the order of 1.5 radian. Phase standard deviations below about 1.2 indicate that the regression was successful, i.e. the unwrapping problem could be solved and the fit matches reasonably the observations. A phase standard deviation of 1.0 indicates a more robust quality. In the case of ERS a phase standard deviation of the order of 0.6 radian is typical for the unfiltered phases of point pairs. Spatial filtering permits to further reduce this phase noise. One objective of filtering is to make the regression analysis more robust.

The phase standard deviation depends on the quality of the reference point as well as on the second point. Consequently, the selection of a high quality reference point in def_mod_pt and multi_def_pt is important to avoid introducing unnecessary high phase noise of the reference point. One possibility to reduce the phase noise of the reference point is to replace the differential interferogram values of the reference with a spatially filtered value (supported by program spf_pt).

## Residual phase – atmospheric phase:

The residual phase contains the atmospheric phase, which is related to the path delay heterogeneity at the two acquisition times of the pair, as well as non-linear deformation and error terms. Different phase terms can be discriminated based on their differing spatial and temporal dependencies. The atmospheric path delay is low-pass in the spatial dimension, but uncorrelated from pass to pass. The non-linear deformation is generally low-pass in the spatial and temporal dimensions, but there may be cases where this is clearly not the case. Baseline related errors are low-pass in the spatial dimension and uncorrelated from pair to pair. Finally, the phase noise is random in both spatial and temporal dimensions.

Programs for spatial and temporal filtering (spf_pt, tpf_pt) and linear combination (lin_comb_pt) are included in the IPTA to support the estimation of the atmospheric phase based on the residual phase. As a quite general approach to this separation we suggest the following steps:

1) Spatial filtering of the residual phases to suppress phase noise (using spf_pt).
2) Temporal filtering of the resulting spatially filtered residual phases to identify trends which are present over some time interval (using tpf_pt). Such phase trends correspond to non-linear deformation (which is present over several observations).
3) Calculation of the complement to the phase trends by subtracting the phase trends from the spatially filtered residual phases. This complement corresponds to parts which are not correlated in time (as assumed for the atmospheric effects) using lin_comb_pt.
4) Spatial filtering of this temporally uncorrelated phase to retrieve an estimate for the atmospheric phase term (using spf_pt).

The trade-off between different terms is determined by setting the related window sizes and weights accordingly.

An alternative approach is to convert the residual phase to 2D raster format and then to apply band-pass filtering tools as supported in the GAMMA ISP.

In this process it has to be kept in mind that other components may have similar characteristics as the ones assumed for the atmospheric phase term, i.e. spatially correlated (low frequency) and temporally uncorrelated (high frequency). An error in the baseline, for example, introduces a large scale (low frequency) phase trend. As the baseline error is not correlated with the other pairs this error is temporally uncorrelated. Consequently, it can be expected to pass the criteria used to separate the atmospheric phase term.

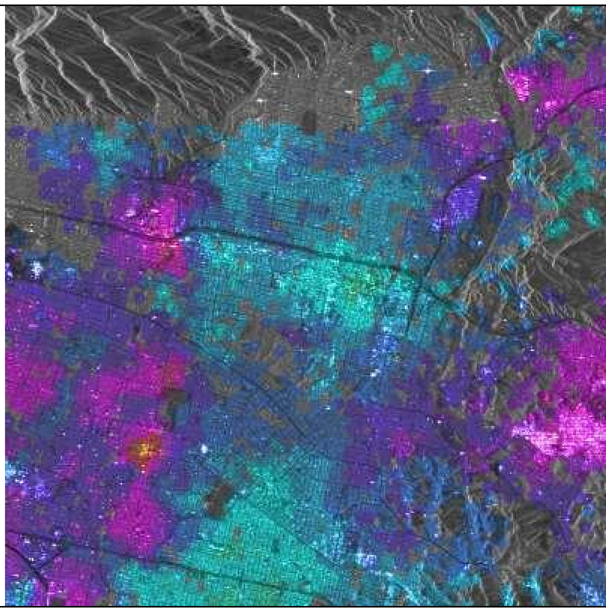
So far we only mentioned an atmospheric phase term without defining exactly if this shall be related to the path delay of a single SLC or of the path delay of the two SLCs of the pair. In fact, this depends on the set of interferometric pairs defined in the itab.

In the case of a stack with a single reference used for all pairs the two-dimensional regression plane does not go through 0.0 radian for zero time and zero baseline, but the plane has an offset which is very directly related to the atmosphere and phase noise of the corresponding point of the reference SLC. The value of the reference SLC is present in each pair, therefore its atmospheric and noise related phase is present in each pair, resulting in an overall offset of the regression plane. For symmetry reasons each other offset from the regression is related to the atmospheric and noise related phase of the corresponding SLC. This means that the atmospheric phases derived from the residual phases will correspond to the atmospheric phases of the individual SLCs, with the one of the record with the auto-interferogram corresponding to the atmospheric and noise related phase of the reference SLC.

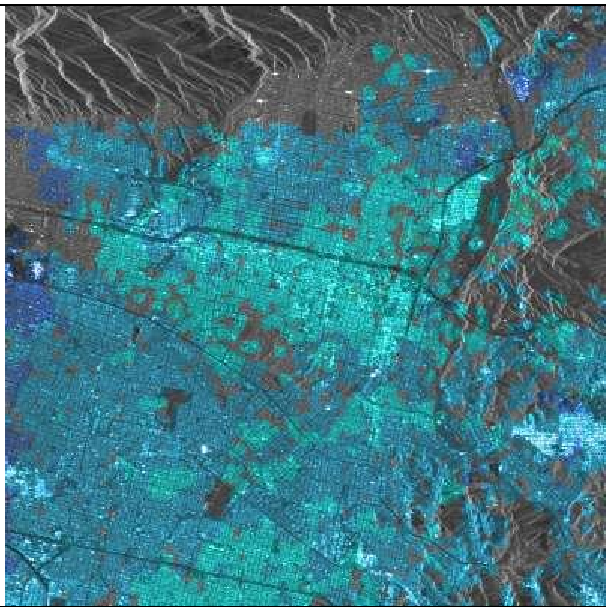
In the case of a stack containing each pair possible with the available SLC the two-dimensional regression plane goes through 0.0 radian for zero time and zero baseline. Offsets from the regression plane are related to the combined atmospheric and noise related phases (i.e. the one of the interferograms), respectively to the difference between the atmospheric and noise related phases of the corresponding reference and slave SLCs. This means that the atmospheric phases derived from the residual phases will correspond to the atmospheric phases of the interferograms. The one of the record with the auto-interferogram should contain a very small offset only.

The combined atmospheric phase term for an interferogram is the difference between the atmospheric phases of the corresponding reference and slave SLCs. In the case of a stack with a single reference used for all pairs this means that the atmospheric phase of the reference SLC needs to be subtracted from all other records to simulate the total atmospheric phase of the interferograms (using lin_comb_pt).

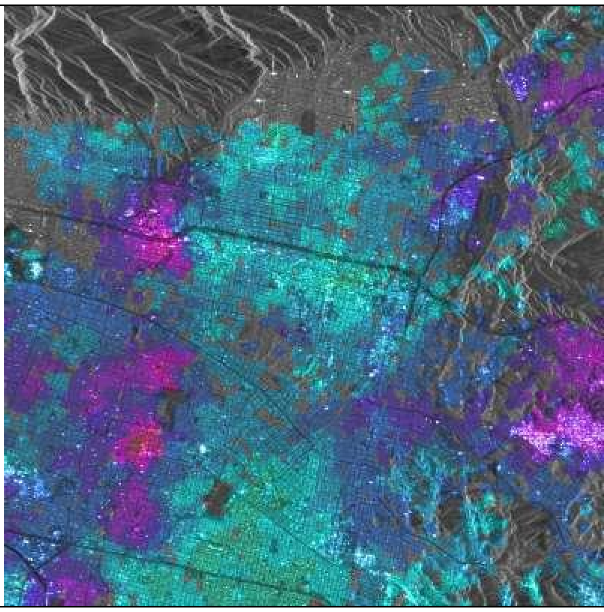
As an example, the residual phase, the temporally and spatially filtered residual phase (= temporally correlated term) and the resulting atmospheric phase term is shown below.



Residual phase (record 23) after spatial filtering. One color cycle corresponds to 2PI.



Residual phase (record 22) after spatial and temporal filtering. One color cycle corresponds to 2PI. Most of the phase is temporally uncorrelated. In this case 10 scenes were included in the temporal filtering.



Atmospheric phase term (record 22) obtained by spatial filtering of the difference between the unfiltered residual phase and the spatially and temporally filtered residual phase. One color cycle corresponds to 2PI. As most of the residual phase is temporally uncorrelated the result corresponds quite closely to the total residual phase.

## Unwrapped interferometric phase:

The regression analysis provides for the differential interferograms the unwrapped phases. The unwrapped phase of the original interferograms is calculated by addition of the unwrapped phases of the differential interferogram and the unwrapped phases calculated in the simulation (using lin_comb_pt or sub_phase_pt).

To assess reliable, interpretable unwrapped interferometric phases is one major step in the IPTA. The other major step is the interpretation of these phases with respect to height, deformation, atmosphere, baseline, and noise.

---

# Iteration concept

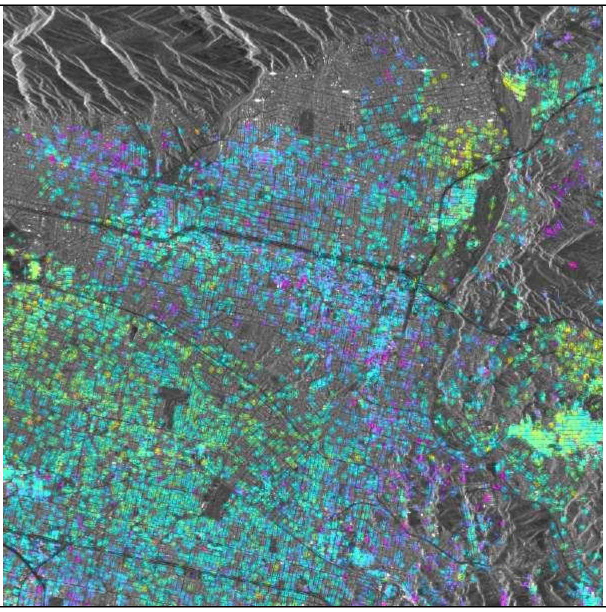
The objective of the iteration concept is a step-wise improvement of the information retrieval. This includes increasing the accuracy of the parameter estimates as well as the spatial coverage, respectively the number of points which can be reliably interpreted. The iteration concept is indicated in Figure 1 by the arrows on the right side of the flow chart. There are different types of iteration. In the plot the type 1 stands for an iteration without change of the point list and type 2 for an iteration which also includes an expansion of the point list.

There is not one correct or recommended order for the iteration. The optimal solution may be different for different cases and may depend on what data and auxiliary information is available. The discussion below describes how a certain parameter is iteratively improved.

## Updating of height and linear deformation model:

It is quite clear that updated heights and linear deformation rates are used to improve the simulated unwrapped phases. In a first iteration the use of an updated height and linear deformation model has the following two main effects:

1) The differential interferograms should all look smooth, even for large baselines. This may serve as a confirmation for the height corrections determined. An example of a large baseline interferogram calculated using the simulated phase after a first height and deformation rate update is shown below. The phase noise previously present was successfully removed.
2) The slopes of the regression planes will be very small after making the main corrections to the model. Consequently, unwrapping will no longer be an issue in the regression step.



ERS differential interferogram as obtained after first update of heights and deformation rates for a pair number 22 with a long baseline (-1179 m) is shown. One color cycle corresponds to 2PI interferometric phase. The high point wise phase noise observed in the initial run is no longer present. The relatively smooth and consistent phase image confirms interpretability of this large baseline interferogram.

## Precision baseline estimation:

The main effect of small baseline errors are large scale phase ramps. For points which are far from each other such phase ramps introduce noise-like errors (as the error is not correlated in time). In the presence of such errors it is essential to use a local enough reference, as supported in the program multi_def_pt.

The objective of the precision baseline estimation is to identify baseline errors and to correct the baseline model so that related phase ramps disappear. This is done using the program base_ls_pt. As input an initial baseline estimate, unwrapped interferometric phases and reference heights are required. The interferometric phase should not be affected by deformation. Areas of non-zero deformation should either be negligible (much smaller than stable area), or they should be masked out for the precision baseline estimation, or the effect of the deformation should be compensated for by subtracting the expected deformation phase.

On the large scale the reference heights should be correct (no tilts etc.). For large areas (full frame or significant portion of a frame) the precision baseline estimation accuracy is therefore higher than for small areas. A constant height offsets and local statistical errors are less important.

Atmospheric path delay heterogeneity affects the precision baseline estimation in two ways. Large scale trends (linear and quadratic in both directions) can be compensated for by modifying the baseline accordingly. This means that a real linear trend in the atmospheric phase will be removed through an adjustment of the baseline. This is of course mainly an issue to be considered if the objective is to retrieve quantitative information on the atmosphere. Furthermore, more random parts of the atmospheric path delay heterogeneity will act as statistical noise in the precision baseline estimation.

Similarly, large scale phase trends (linear and quadratic in both directions) originating from surface deformation can be compensated for by modifying the baseline accordingly. This means that a real linear trend in the atmospheric phase will be removed through an adjustment of the baseline, leading to the above mentioned requirement that the phases should not be affected by deformation (at least not in a systematic way).

For these reasons the precision baseline estimation should be done based on unwrapped interferometric phases which are not affected systematically by deformation. Height references which are correct on the large scale should be used. Using an initial baseline estimate of high quality (as obtained for ERS when using PRC or DELFT precision state vectors) is an advantage.

In the case of state vectors of only moderate accuracy (e.g. JERS), it may be necessary to first improve the initial baseline estimate, for example based on the large scale phase trend as supported by the program base_init of the GAMMA ISP.

The precision baseline estimation is qualified with the standard deviation between the calculated interferometric heights and the reference heights. In the case of very short baselines this may include a few quite large numbers, but corresponding to small phase standard deviations.

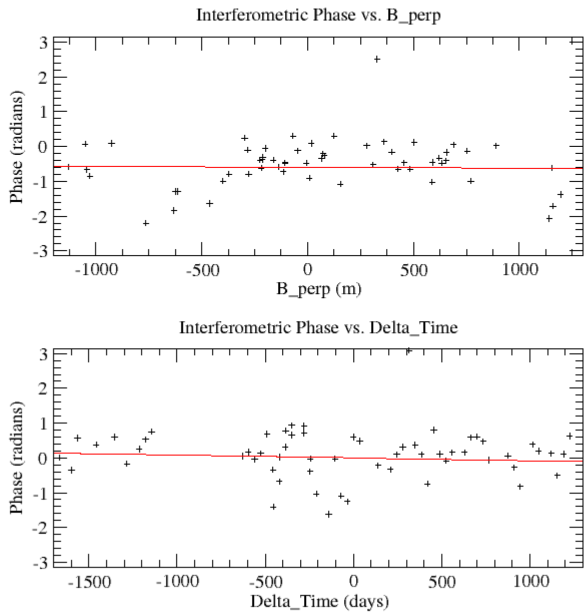
An important aspect of the precision baseline estimation is that large scale trends in the individual differential interferograms are removed which is a pre-condition for the interpretation of pairs with wider spatial separation, such as required when moving form a local to a global reference.

## Subtraction of atmospheric phase:

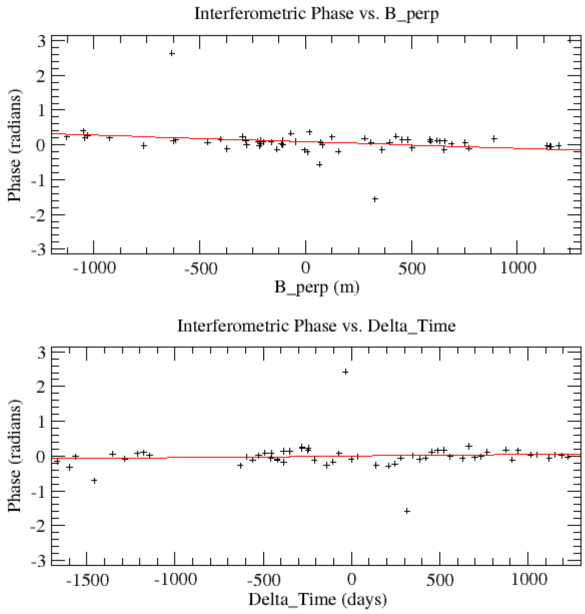
As mentioned before atmospheric phase terms are spatially low frequency and temporally uncorrelated (high frequency). Based on these characteristics they can be estimated from the residual phases as described above. Depending on the type of stack this results either in the atmospheric phase terms of the individual SLC, which need to be combined to retrieve the atmospheric phase terms of the interferomgrams, or directly to the atmospheric phase terms of the interferomgrams.

The main effect of the atmospheric phase terms is that it introduces significant noise-like phase errors for pairs of wider spatial separation. In the presence of such errors it is essential to use a local enough reference, as supported in the program multi_def_pt. The removal of the atmospheric phase term is a pre-condition for the interpretation of pairs with wider spatial separation, such as required when moving form a local to a global reference (multi_def_pt to def_mod_pt).

The second objective is to reduce the error of the interferometric information. For interpretable interferometric phases the atmospheric phase term is the main error source. Having several observations and assuming certain characteristics for the signal and the atmospheric phase term permits to reduce this error.




IPTA phase regression plot for point pair separated by long distance, done after baseline refinement and subtraction of atmospheric phase terms. The phase standard deviation is 0.71 radian.



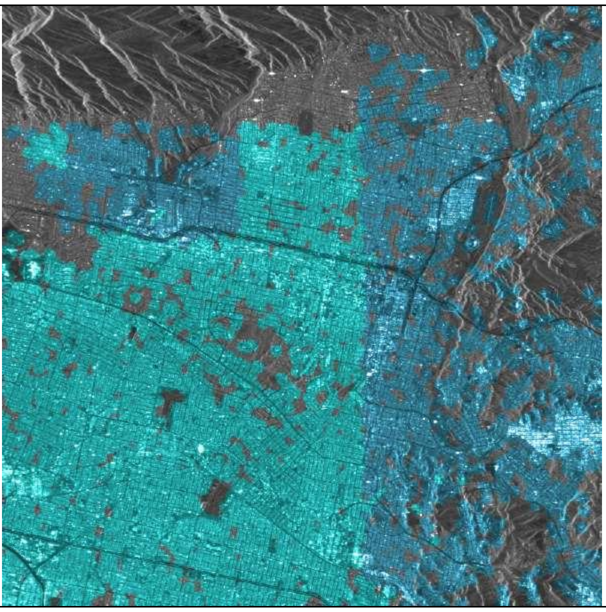

Same as previous plot, but for spatially filtered differential interferogram. Phase noise is significantly reduced. Temporal behavior corresponds not to single point but to average behavior of a group of points in the close neighborhood of the selected point pair. The phase standard deviation is 0.41 radian.

## From local to global reference:

Errors in the baseline and the atmospheric term cause strong phase variations at large distance. The use of a local reference is therefore essential. Once these effects have been included in the phase model the differential interferograms should all become almost flat with only minor phase variations. At this stage a single global reference point can be used for all other points. This permits to avoid patching effects (which may be present when using multi_def_pt).

The selection of a high quality reference is important.

An example of a patching effect in the deformation rate correction obtained in a second iteration is shown below. The amplitude of the effect is slightly below 0.5 mm/year.



A patching effect is clearly visible in this deformation rate correction obtained in a second iteration. The darker blue areas have a deformation rate offset of around 0.5 mm/year due to the phase noise of the reference points used in the patch to patch propagation.

## Expansion of point list:

The role of the expansion of the point list is to identify points with interpretable phases as completely as possible. The criteria used is the phase standard deviation from the model itself. To do this efficiently, not each image point, but just points of a candidate list are used. This candidate list should include all points with interpretable phases, but it may also include many points which are not acceptable for the IPTA.

The program used for the point list expansion is expand_pt. In addition, to the large candidate list, a list of qualified, high quality, points is provided. These high quality points are used as reliable local references for the qualification of the candidates of the large list.

Information derived for the smaller list may be interpolated to the extended list coordinates and used as input for an initial iteration using the extended list.

---

# Post-processing and display

The main interest in the IPTA is to explain the observed phases versus real-world physical parameters. In the iteration the phase model is improved to match the observations as good as possible. The deviation from the model is not just the error or uncertainty, but it is an important part of the information as it contains the non-linear part of the deformation.

At the end of the iteration the following data sets are available in the IPTA point data format:

- final linear deformation rates (single record),
- final terrain heights (single record),
- final atmospheric phase terms (multiple records),
- final baseline estimates (for each interferogram record)
- final residual phases (i.e. deviations from final model, multiple records).

Based on linear deformation rate the deformation phase for each record is calculated using the program phase_sim_pt. These deformation phases and the residual phases are added, leading to the total deformation phases. In the case of a single reference SLC used in all pairs, this corresponds directly to the deformation phase history. The residual phases also include the residual phase errors caused by errors in the phase model parameters and phase noise, so these terms will be part of the deformation phase history.

Depending on the exact requirements the deformation phase history may be filtered to reduce phase noise. This can be done in the spatial (spf_pt) as well as in the temporal (tpf_sp) direction. For regional effects filtering is suggested, because the phase noise is reduced. But to observe single point effects spatial filtering is not adequate at all. So, we recommend to consider both the filtered and unfiltered deformation history.

As for the linear deformation rates, the terrain heights may be spatially filtered. In the interpretation of the terrain heights it is important to remember that many scatterers are related to buildings. Some of the scatterers are located at ground level, while others are found at roof level. Consequently, single point effects to the terrain height of up to more than 10m are observed.

The atmospheric phases are already spatially filtered.

After these steps the result consists of the following data sets which are available in the IPTA point data format:

- final linear deformation rates (single record, filtered and/or unfiltered),
- final terrain heights (single record, filtered and/or unfiltered),
- final atmospheric phase terms (multiple records),
- final baseline estimates (for each interferogram record),
- deformation phase history (multiple records, filtered and/or unfiltered),

In addition, quality information and unwrapped differential phases are available.

The result depends on the iteration scheme, the processing settings, and the filtering used. All these should reflect the information requirements of the specific case.

An important aspect to consider carefully is the use of reference values. The primary interest is not so much in a model which well describes the observed phases, but physical parameters which correspond to the real world.

Height references are used in the baseline refinement. Apart from a height offset linear and quadratic phase trends may be compensated for in the baseline refinement. This means that a linear trend in the atmospheric phase term (i.e. a large scale phase ramp) and also in the deformation rate may be compensated for by adjusting the baselines accordingly. It is therefore important not to include instable points in the baseline refinement or to compensate their phases for the deformation term. It also needs to be considered that the height corrections derived are relative to the selected reference point. The height of this reference point may be affected by single point effects, i.e. its height may differ from the corresponding terrain height.

The deformation phase histories are relative to the selected reference point. If this point is not stable its deformation has to be added to all the other deformation values. Apart from using this reference point, usually, no other deformation references are used explicitly. But, as indicated above, large scale trends (linear and quadratic) may be compensated for by adjusting the baselines accordingly. This means that the assumption used is that the points considered in the baseline refinements are overall stable, respectively follow the trend the phase was corrected for. Caution is required in these steps and the user of the software has to be aware that multiple models may explain the observed phases. In the case of a large scale linear trend in the deformation rate this trend may get lost in the processing, respectively it may be hidden by related adjustments to the baselines. To avoid such errors it is important which points and phases are used in the baseline refinement. It is furthermore important to be aware that the atmospheric phases may include large scale and temporally correlated trends.

Approaches to reduce such problems include:

- awareness of references used,
- awareness of model assumptions used,
- use many scenes (improves statistics),
- use of large area (better for baseline estimation, trends are reduced on larger scale, more stable areas may be included)
- use accurate references.

Stating these potential problems of the IPTA analysis may give the impression that everything remains very uncertain what concerns the usefulness of the IPTA, its robustness and the quality of the information derived. In fact, the main strength of the IPTA is that more data can be used in the interpretation which is exactly what is essential to minimize such problems. Furthermore, the IPTA addresses the related issues in a more structured way than usually done in conventional differential interferometry, which improves the awareness of possible problems.

## Access of result and display:

The main information derived with IPTA for a specific case includes only a few point data files such as the deformation history. To access the information content tools are required. The IPTA includes tools to convert image data records from the point based vector data format to 2D raster data format (pt2data, pt2d). These tools also include interpolation and filtering functionality, or such operations can be applied separately using other tools, either in the point data format or after the transformation in the 2D images. Images in the 2D raster geometry can be visualized or converted to SUN or BMP rasterfiles using the programs of the GAMMA software.

The IPTA also includes tools to extract time series for specific points (dis_IPTA_unw, prt_pt, prox_prt). The values may be written to ASCII files. Related plots can be displayed using XMGRACE.

One important way to use the data is to keep the information in the IPTA format and to access it interactively using programs as dis_IPTA_unw.

To geo-reference the information there are currently two possibilities. One is to geocode the results in 2D raster format using the GAMMA GEO or DIFF&GEO software. The other possibility is to identify the lookup table values at the point coordinates. Together with the related DEM parameter file these indicate the map coordinates of the points. Of course the height correction derived with IPTA and a lookup table after fine registration should be used.

---