Interferometric Point Target Analysis for Deformation Mapping

Charles Werner, Urs Wegmüller, Tazio Strozzi, and Andreas Wiesmann
Gamma Remote Sensing, Thunstrasse 130, CH-3074 Muri, Switzerland
http://www.gamma-rs.ch e-mail: cw@gamma-rs.ch

Abstract—

Keywords: Interferometric point target analysis (IPTA), subsidence, surface deformation, terrain heights, atmospheric path delays.

I. Introduction

Repeat-pass space-borne interferometric SAR is a powerful technique for the observation of land surface deformation [1]. Causes for deformation include tectonic, seismic, and volcanic activity, ice and rock glacier motion, slope instability, and subsidence caused by ground water pumping, mining, hydrocarbon extraction, and natural compaction. A major advantage of this technique is its two-dimensional spatial coverage as compared to point-wise measurement techniques such as leveling and GPS.

An important problem for SAR interferometry is decorrelation. Temporal decorrelation occurs from changes in the scatterer characteristics. Vegetation, for example, causes significant decorrelation that often completely prevents from interpretation of interferometric phases of pairs with long acquisition time differences. Spatial decorrelation prevents interpretation of interferometric phases for extended targets in pairs with long baselines. Low coherence may also result in phase unwrapping problems, especially in the presence of high phase gradients.

In areas of sufficient coherence and after spatial filtering to reduce phase noise, the main error source is the heterogeneity in the atmospheric path delay. Techniques for reducing this error by stacking multiple independent observations have been presented and have achieved validated accuracies in the mm/year range [2-4].

Ferretti et. al. [6,7] proposed examining interferometric phases from stable, point-like reflectors and demonstrated that large numbers of such reflectors could be identified in stacks of ERS data, particularly in build-up areas. For point targets no spatial decorrelation occurs permitting interpretation of the interferometric phase of pairs with long baselines, even above the critical baseline. Obviously same reflector must remain stable over the time period of interest to permit analysis of the phase history.

Building upon these ideas [2-7] the main objective of our development is to achieve 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.

In the following sections our Interferometric Point Target Analysis (IPTA) concept is presented. Data examples are used to illustrate intermediate and final products and to confirm the validity of the concept.

II. IPTA Concept

A. Data management

In the interferometric point target analysis the interferogram is 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.

B. Interferometric phase model

The phase model used for the IPTA is the same as conventional interferometry. The unwrapped interferometric phase ϕ_{unw} is expressed as the sum of topographic ϕ_{topo}, deformation ϕ_{def}, differential path delay (also called atmospheric phase) phase ϕ_{atm}, and phase noise ϕ_{noise} (or decorrelation) terms:

$$\phi_{unw} = \phi_{topo} + \phi_{def} + \phi_{atm} + \phi_{noise} \, . \qquad (1)$$

Also important in the context of the phase model are spatial and temporal characteristics of the different terms. For example ϕ_{atm} can be considered *low-pass* in the spatial domain and *high-pass* (random) in the temporal domain.

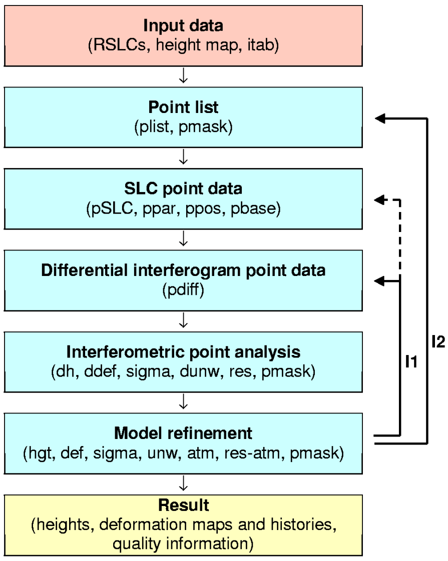

Figure 1: Interferometric point target analysis (IPTA) processing approach.

C. Processing sequence

An overview on the IPTA processing sequence is given in Fig. 1. The IPTA processing begins by assembling a stack of co-registered single look complex images (RSLCs), the related SLC and orbit parameters (pSLC_par), and a text file (itab) that is used to specify which pairs shall be considered in the interferometric data stacks. For a large stack of more than 10 SLCs a typical selection is that the same reference SLC is used for all pairs. Furthermore, a preliminary Digital Elevation Model (DEM) is used, if available.

Based on the registered SLCs, a candidate list of point targets is determined. Point targets do not show the speckle behavior associated with distributed targets since, by definition, only a single coherent scatterer contributes to the echo. The intensity and phase are directly dependent on the point target radar cross section and position. Consequently, an initial selection of point target candidates can be performed based on the low temporal variability of the backscatter. 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 a later stage of the processing the standard deviation of the phase with respect to the model becomes the selection criteria.

For the candidate points the SLC values are extracted and written to a point data stack. Initial estimates of the interferometric baselines are calculated from the available orbit state vectors.

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 and the quality of the candidate points, these differential interferograms may look smooth or very noisy. In fact for pairs with very large baselines the accuracy requirements for the height are high, so that the related differential interferograms will look noisy (Fig. 3), even when using a high resolution DEM of good quality.

In the next step the stack of differential interferograms is analyzed. 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. 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 ϕ_{noise}, ϕ_{atm}, ϕ_{def}, and baseline errors. Except for ϕ_{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 ϕ_{atm}, ϕ_{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. An example of such a two-dimensional regression analysis is shown in Figure 2. The 59 points correspond to 59 differential interferometric phases. The slope in the upper plot shows that the baseline dependence is quite steep, indicating a height correction of 13.294 m. The lower plot shows a linear phase trend equivalent to a subsidence of 1.96 mm/year. One problem for the regression is that the phases in the differential interferogram 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 detect and reject points which are not suited for IPTA analysis.

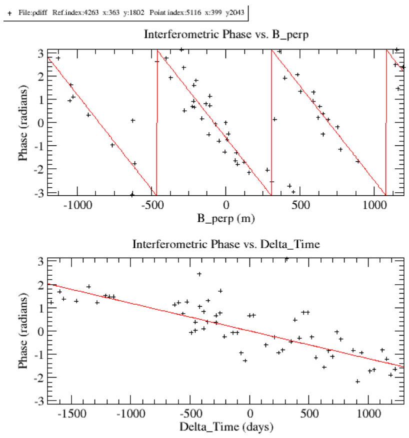

Figure. 2: Two-dimensional regression analysis of differential interferometric phase difference of two close points in a stack of 59 ERS interferograms.

This regression analysis is performed for the entire point list. The results 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. As a validation of the successful improvement of the heights and of the interpretability of the phases of point targets in pairs with very large baselines, Fig. 4

shows the differential interferogram for the same pair as in Fig. 3, but uses the improved heights for the phase model.

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.

D. Iterative improvement of parameters

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 derivation of height corrections and constant deformation rates is done in the two-dimensional regression analysis already described.

For the baseline refinement a least-squares approach based on the unwrapped phases and the corresponding terrain heights is used. Either the original heights or the heights after the height correction can be used. The effect of linear deformation can be compensated for or the estimation can be limited to areas with no deformation.

The atmospheric phase terms are estimated from the residual phases. Discrimination of phase noise from non-linear deformation is done by considering only spectral components that are low frequency in the spatial dimension and high frequency in the temporal dimension. This is done after the refinement of the baselines, as the baseline-related errors would also fall in this spectral category. The correct separation of the atmospheric phase term, the non-linear deformation, and phase noise is not completely possible. The assumptions used in the separation may not be fully valid. To map very fast or very local deformation features the separation criteria need to be adapted accordingly. Fig. 5 shows the differential interferogram for the same pair as in Fig. 3, using the improved heights, the refined baselines, and the correction for the atmospheric phase.

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.

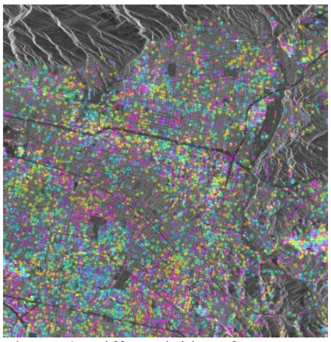

Figure. 3: Differential interferogram with B_perp = 1162.47m

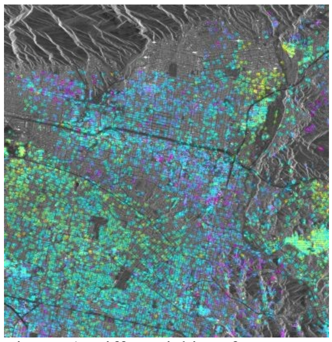

Figure. 4: Differential interferogram of Fig. 3 but using improved heights

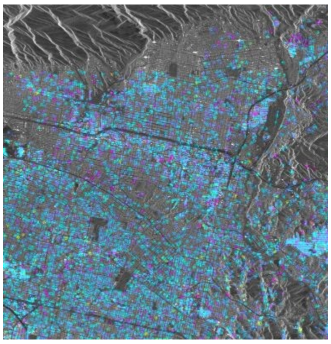

Figure. 5: Differential interferogram of Fig. 3 using improved heights, baseline, and atmospheric terms.

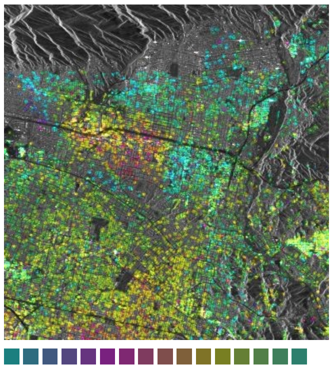

Figure. 6: Linear deformation rate. The central subsiding region is associated with the Raymond Fault zone in south Pasadena.

The IPTA result consists of the improved model, including heights, linear deformation rates (Fig. 6), atmospheric phase, refined baselines, quality information, and non-linear deformation histories for each point.

III. CONCLUSIONS

The IPTA concept was presented and discussed. For a time series of ERS-1/2 data the functionality of the concept was confirmed. The large existing archives of SAR data, particularly for ERS, make IPTA a viable technique for large-scale analysis of surface deformation in urbanized regions.

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