Deformation monitoring using radar interferometric time series: a review of methodologies

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1 Introduction

From the late eighties, Interferometric Synthetic Aperture Radar (InSAR) has been used to measure deformations of the earth's surface (Gabriel et al., 1989). Numerous studies have been reported about the monitoring of the consequences of earthquakes, volcanism, oil or gas extraction, ground water flow, ice motion and geo-technical processes. The results showed that the repeat pass principle applied induces three degrading factors. First, the variable state of the atmosphere in time and space superimposes an error signal that interferes with the deformation signal. Second, the different look angles from the two platforms to the same resolution cell on the ground cause a spectral shift in the observations, resulting in noise denoted as geometric decorrelation. And finally, the scatter characteristics of the earth's surface within a resolution cell change over time, resulting in temporal decorrelation.

The latest developments in InSAR research focus on the reduction of these degrading factors using a multitude of radar acquisitions. Roughly, two different approaches can be distinguished. The *Permanent Scatterer* technique (Ferretti et al., 2000, 2001) focuses on the most stable scatterers in time. These point scatterers are minimally affected by temporal decorrelation and also the effect of geometric decorrelation is strongly reduced. Selecting the most stable scatterers, this approach can be regarded as *top-down*. In contrast, the *short baseline time series* approach (Usai, 2001; Berardino et al., 2002) assumes that contiguous areas remain correlated over time, and only excludes the resolution cells with strong decorrelation. This approach can therefore be denoted as *bottom-up*. The use of interferograms with small baselines obviously reduces the geometric decorrelation. Both approaches are discussed in more detail below. The reduction of atmospheric influences is also addressed. First, the starting point for both approaches, Differential InSAR (DInSAR), is discussed briefly.

2 Differential InSAR

The interferometric phase observation per resolution cell is composed by a number of contributors (Hanssen, 2001)

$$\begin{aligned} \phi &= 2\pi k + \phi_{\text{topo}} + \phi_{\text{defo}} + \phi_{\text{orb}} + \phi_{\text{atm}} + \phi_{\text{scat}} + \phi_{\text{noise}}, \\ &= 2\pi k + \frac{4\pi B_{\perp}}{\lambda R \sin(\theta)} H + \frac{4\pi}{\lambda} D + \phi_{\text{orb}} + \phi_{\text{atm}} + \phi_{\text{scat}} + \phi_{\text{noise}}. \end{aligned} \tag{1}$$

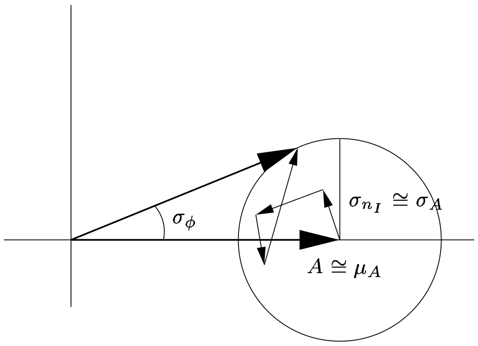
The first term on the right hand side denotes the unknown integer number of full phase cycles or *phase ambiguity.* The topographic phase ϕ_{topo} is a function of the perpendicular baseline $B_\perp$, the look angle for the master platform θ and the slant range from the master platform to the earth's surface R. It describes the height H above a reference surface. Further, ϕ_{defo} is due to deformation D in the radar line-of-sight and ϕ_{orb} comprises the deterministic flat earth component and the residual signal due to orbit errors. This residual signal forms a linear trend in the interferogram and can be estimated and removed beforehand. Alternatively, it can be included in the atmospheric delay ϕ_{atm}, because the atmosphere causes a linear trend as well. Either way, after removal of the flat earth component, the ϕ_{orb} term vanishes. The signal due to a change in the scatter characteristics of the earth's surface between the two observation times is denoted by ϕ_{scat}. Finally, ϕ_{noise} represents the remaining noise terms, caused by e.g., thermal noise, co-registration errors and interpolation errors.
When deformation is the parameter of interest, the topographic phase is to a large extent removed using an external DEM. This technique is known as Differential InSAR. The DEM can be generated using InSAR or by other observation techniques. Advantage of the use of an InSAR based DEM is that the earth is observed with an identical radiometric signal, so that objects are viewed similarly. In the nineties, InSAR DEM generation was a hot topic due to the enormous gain in resolution and coverage that could be obtained. However, after the SRTM mission (Rabus et al., 2003), a semi-global DEM with high accuracy became publicly available, reducing the need for research in this field. After removal of the topographic reference phase, a residual topographic phase is left due to the inaccuracy of the DEM. The differential phase obtained is the starting point for further analysis of the deformation

$$\phi_{\Delta H} = 2\pi k + \frac{4\pi B_\perp}{\lambda R \sin(\theta)}\Delta H + \frac{4\pi}{\lambda} D + \phi_{\text{atm}} + \phi_{\text{scat}} + \phi_{\text{noise}}. \qquad (2)$$

3 Permanent Scatterers

Usai (1997); Usai and Hanssen (1997) were the first to recognize that certain features show a stable phase behavior over long time intervals, that is, ϕ_{scat} remains approximately zero. Many of these features appear to be man-made. The point-like scattering results in a *sinc*-shaped signal in the SAR image and because of it's limited size, geometric decorrelation is minimal. The permanent scatterer technique, proposed by Ferretti et al. (2000, 2001), uses these points to estimate the deformation *profile.* The deformation profile shows the detailed development of the deformation, sampled at the epochs.

The first step is the identification of an initial set of permanent scatterers, the permanent scatterer candidates (PSC), conserving the high spatial resolution. Because the permanent scatterers are assumed not to be affected by temporal and geometric decorrelation, the whole set of available acquisitions can be used, including those causing large temporal and spatial baselines. Typically, at least 30 acquisitions are necessary. Because it is not possible to detect points with stable scatter behavior from the differential interferometric phase observables (Eq. (2)) directly, Ferretti et al. (2001) propose to use the stability of the amplitude A as an indicator for phase stability. Assuming circular Gaussian noise for the real and imaginary part of the signal (σ_{n_R} and σ_{n_I}), the phase dispersion can be approximated by the amplitude dispersion D_A



$$\sigma_\phi \cong \frac{\sigma_{n_I}}{A} \cong \frac{\sigma_A}{\mu_A} \doteq D_A, \tag{3}$$

where σ_A and μ_A are the amplitude standard deviation and mean in time per resolution cell. An amplitude dispersion of 0.25 is a typical threshold. For a more refined selection, additional constraints can be formulated, such as a minimal amplitude in a minimal number of interferograms (Kampes and Adam, 2003). Obviously, the interferograms have to be co-registered on the same grid with high precision. Originally, Ferretti et al. (2000, 2001) use a single master configuration, but other baseline configurations have been reported as well (Lanari et al., 2003).
An alternative procedure to select the PSC is the analysis of the signal-to-clutter ratio (SCR) (Adam et al., 2003). Numerical studies show that the performance is better compared to the use of the amplitude dispersion. However, the calculation of the SCR requires the occurrence of clutter in the surroundings of the permanent scatterer, which might not be the case in densely urbanized areas.

Once the PSC have been selected, the various phase components (Eq. (2)) can be estimated. Often, a network of phase gradients is constructed by a Delauney triangulation. Due to the use of gradients, possible constant phase offsets between interferograms are eliminated and the effects of orbit errors and atmosphere are minimized. Unfortunately, the phase ambiguity induces a non-linear problem. Ferretti et al. (2000, 2001) use a 2D periodogram technique to maximize the time-coherence as function of the linear deformation rate and DEM error. Basically, a 2D space is searched for the optimal solution. Colesanti et al. (2003) estimate two additional parameters to describe a seasonal deformation effect. However, for the periodogram technique, the computational burden increases proportionally with the number of parameters estimated. The remaining phase components, ϕ_{atm}, $\phi_{\text{defo,non-linear}}$ and ϕ_{noise}, are regarded as residual signal and are separated in a sequential filtering step. Because these components are relatively small (typically $< \pi$), at this stage the phase can easily be unwrapped by integration of the gradients. The precision of the estimates was first assessed by Colesanti et al. (2003).
As an alternative, Hanssen et al. (2001); Bianchi (2003); Kampes and Hanssen (2004) use a least-squares integer estimation technique, which is successfully applied in GNSS processing. However, due to the lack of redundant observations, implementation for InSAR is not straightforward and pseudo-observables have to be used. Nevertheless, promising results have been obtained, enabling the efficient estimation of additional parameters, such as the atmospheric signal during the master acquisition or a non-linear deformation pattern (Kampes and Hanssen, 2004). Moreover, a quality description is obtained, enabling the integration with other geodetic observations.

Regardless the method chosen, the residual signal can be filtered to extract the atmospheric signal per acquisition (Ferretti et al., 2000). Here, the correlation of the atmosphere in space and the decorrelation in time is utilized. A combined smoothing and interpolation operation using Kriging gives the atmospheric signal for the whole scene. After subtraction of the atmospheric phase from the original differential phase, the estimation procedure can be repeated for all pixels. After estimation of the parameters, the phase stability can be assessed to select the permanent scatterers. For each permanent scatterer a deformation profile is now obtained. The permanent scatterer density depends on the urbanization degree of the area.

4 Short baseline time series

The short baseline time series approach also uses a multitude of interferograms to estimate deformations. The short baselines (typically < 200 m) reduce the geometric decorrelation. Furthermore, the sensitivity for DEM errors is strongly reduced, due to the large *height ambiguity*. The height ambiguity is the height which induces a full phase cycle (see Eq. (1)). In contrast to the permanent scatterer technique, the selection of usable resolution cells is based on spatial coherence in certain windows. This windowing reduces the resolution (typically > 80 m^2), however, due to the multi-look the noise reduces as well.

From the time series, a linear trend or a more detailed profile of the deformation can be estimated. *Stacking* is a very simple, but effective way to derive a linear deformation. More sophisticated methods have been derived to estimate the deformation profile.

4.1 Stacking

When a linear deformation pattern is suspected during a certain period, a number of interferograms covering parts of this period can be added, weighted by their individual time span. Deviation by the total time span gives the deformation rate (e.g., per year). Due to the weighted averaging and the use of overlapping interferograms in time, the atmospheric delay is assumed to be averaged out. Possible DEM errors are small due to the large height ambiguity and are therefore neglected.

Often the phase is assumed to be unwrapped beforehand. Then, either interferograms from independent acquisition pairs (Bürgmann et al., 2000; Wright et al., 2001; Mouélic et al., 2002) or interferograms with communal acquisitions (Zebker et al., 1997; Lyons and Sandwell, 2002) can be stacked. The latter endangers the multiple addition of an acquisition with a strong atmospheric signal.
Unwrapping of the phase beforehand is not necessary applying the gradient approach (Sandwell and Price, 1998). Here, the gradients between neighboring resolution cells are stacked. However, comparison of the results with other geodetic techniques requires an unwrapping step afterward.

4.2 Profile estimation

When a better understanding of the deformation pattern is required, a detailed deformation profile can be estimated. The estimation, possibly including the DEM error, is either based on the periodogram technique described for the permanent scatterer analysis (Mora et al., 2003; Altamira, 2004) or on a least-squares inversion (Usai, 2001; Berardino et al., 2002; Schmidt and Bürgmann, 2003; Hoffmann, 2003). The latter requires phase unwrapping beforehand. In both cases, as much interferograms as possible are generated from the selected acquisitions. As a result, Mora et al. (2003) state that less acquisitions are needed than for a permanent scatterer analysis, although addition of acquisitions will improve the result. However, none of the references take the correlation between interferograms sharing an acquisition into account. The atmospheric effect can be estimated using the filtering technique described for the permanent scatterer analysis (Ferretti et al., 2000).

The constraint of using small baselines might imply that not all acquisitions of the same area can be used. In order to make full use of the available acquisitions, multiple subsets with small baselines can be constructed. A number of strategies to link these subsets have been proposed. Berardino et al. (2002); Mora et al. (2003) use a Singular Value Decomposition (SVD), resulting in a minimum norm solution. Costantini (2003) proposes a minimum curvature norm. Usai (2003) simulates an acquisition in the main set, based on linear interpolation between two (short time separated) actual acquisitions, to link two sets. Like for permanent scatterers, the full set of acquisitions can now be exploited.

5 Conclusions

The two main methodologies to monitor deformation of the earth's surface are the permanent scatterer technique and the short baseline time series approach. Both methods select the most suitable resolution cells, either top-down or bottom-up. In both cases it is possible to estimate a detailed deformation profile. The advantages of the permanent scatterer technique are that the full resolution of the interferograms is preserved, all acquisitions can be used without (arbitrary) linking using a specific norm as in the short baseline time series case and that the phase does not need to be unwrapped beforehand. The 2D periodogram technique gives satisfying results, however, integer least-squares estimation gives the opportunity for a profound quality assessment. On the other hand, the short baseline time series approach has a lower computational burden due to the reduced resolution, or equivalently, enables the coverage of a larger area. Moreover, the noise reduction due to multi-looking might imply a denser coverage of usable resolution cells in the area.

Interesting question is which approach performs best under certain circumstances, that is, for different degrees of urbanization and different deformation processes. To assess this, certainly the correlation between interferograms should be taken into account. Possibly, a combination of methods, like described by Lanari et al. (2003) forms an alternative. Here, the large scale deformation patterns are estimated using the short baseline approach, whereas the local phenomena are estimated by permanent scatterer analysis.

A team of researchers working on radar interferometry within the Delft institute for Earth Observation and Space systems (DEOS) of Delft University of Technology is going to further develop the theory of monitoring deformation of the earth surface using InSAR. Especially the quality assessment of the estimations will get attention. Real data will be used to validate the methods, with special attention for interesting areas in the Netherlands.

References

Adam, N., Kampes, B. M., Eineder, M., Worawattanamateekul, J., and Kircher, M. (2003). The development of a scientific permanent scatterer system. In *ISPRS Workshop High Resolution Mapping from Space, Hannover, Germany, 2003*, page 6 pp.

Altamira (2004). ENVISAT-ERS exploitation: development of algorithms for the exploitation of ERS-ENVISAT using the stable points network. Technical Report 16702/02/I-LG, ESA.

Berardino, P., Fornaro, G., Lanari, R., and Sansosti, E. (2002). A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Transactions on Geoscience and Remote Sensing*, 40(11):2375–2383.

Bianchi, M. (2003). Phase ambiguity estimation on permanent scatterers in SAR interferometry: the integer least-squares approach. Master's thesis, Politecnico di Milano/Delft University of Technology.

Bürgmann, R., Schmidt, D., Nadeau, R. M., d'Alessio, M., Fielding, E. J., Manaker, D., McEvilly, T. V., and Murray, M. H. (2000). Earthquake potential along the Northern Hayward Fault, California. *Science*, 289:1178–1182.

Colesanti, C., Ferretti, A., Novali, F., Prati, C., and Rocca, F. (2003). SAR monitoring of progressive and seasonal ground deformation using the Permanent Scatterers Technique. *IEEE Transactions on Geoscience and Remote Sensing*, 41(7):1685–1701.

Costantini, M. (2003). A curvature based method for processing of multi-temporal SAR differential interferometric measurements. In *Third International Workshop on ERS SAR Interferometry, 'FRINGE03', Frascati, Italy, 3-5 Dec 2003.*

Ferretti, A., Prati, C., and Rocca, F. (2000). Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, 38(5):2202–2212.

Ferretti, A., Prati, C., and Rocca, F. (2001). Permanent scatterers in SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, 39(1):8–20.

Gabriel, A. K., Goldstein, R. M., and Zebker, H. A. (1989). Mapping small elevation changes over large areas: differential radar interferometry. *Journal of Geophysical Research*, 94(B7):9183–9191.

Hanssen, R. F. (2001). *Radar Interferometry: Data Interpretation and Error Analysis.* Kluwer Academic Publishers, Dordrecht.

Hanssen, R. F., Teunissen, P. J. G., and Joosten, P. (2001). Phase ambiguity resolution for stacked radar interferometric data. In *International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation, Banff, Canada, 5–8 June 2001*, pages 317–320.

Hoffmann, J. (2003). *The application of satellite radar interferometry to the study of land subsidence over developped aquifer systems.* PhD thesis, Stanford University.

Kampes, B. M. and Adam, N. (2003). Velocity field retrieval from long term coherent points in radar interferometric stacks. In *International Geoscience and Remote Sensing Symposium, Toulouse, France, 21–25 July 2003*, pages cdrom, 4 pages.

Kampes, B. M. and Hanssen, R. F. (2004). Fast ambiguity resolution for permanent scatterer interferometry. *To be submitted.*

Lanari, R., Mora, O., Manunta, M., Mallorqui, J. J., Berardino, P., Guarino, S., Zeni, G., Pepe, A., and Sansosti, E. (2003). A differential SAR interferometry approach for monitoring urban deformation phenomena. In *Second GRSS/ISPRS Joint Workshop on "Data Fusion and Remote Sensing over Urban Areas", Berlin, Germany, 22–23 May, 2003*, pages 57–61.

Lyons, S. and Sandwell, D. (2002). Fault creep along the southern San Andreas from InSAR, permanent scatterers, and stacking. *Journal of Geophysical Research*, submitted(?):?

Mora, O., Mallorqui, J. J., and Broquetas, A. (2003). Linear and nonlinear terrain deformation maps from a reduced set of interferometric SAR images. *IEEE Transactions on Geoscience and Remote Sensing*, 41(10):2243–2253.

Mouélic, S. L., Raucoules, D., Carnec, C., King, C., and Adragna, F. (2002). A ground uplift in the city of Paris (France) revealed by satellite radar interferometry. *Geophysical Research Letters*, 29:1853.

Rabus, B., Eineder, M., Roth, A., and Bamler, R. (2003). The shuttle radar topography mission—a new class of digital elevation models acquired by spaceborne radar. *ISPRS Journal of Photogrammetry and Remote Sensing*, 57:241–261.

Sandwell, D. T. and Price, E. J. (1998). Phase gradient approach to stacking interferograms. *Journal of Geophysical Research*, 103(B12):30183–30204.

Schmidt, D. A. and Bürgmann, R. (2003). Time-dependent land uplift and subsidence in the Santa Clara valley, California, from a large interferometric synthetic aperturee radar data set. *Journal of Geophysical Research*, 108(B9):doi:10.1029/2002JB002267.

Usai, S. (1997). The use of man-made features for long time scale insar. In *International Geoscience and Remote Sensing Symposium, Singapore, 3–8 Aug 1997*, pages 1542–1544.

Usai, S. (2001). *A New Approach for Long Term Monitoring of Deformations by Differential SAR Interferometry.* PhD thesis, Delft University of Technology.

Usai, S. (2003). A least squares database approach for SAR interferometric data. *IEEE Transactions on Geoscience and Remote Sensing*, 41(4):753–760.

Usai, S. and Hanssen, R. (1997). Long time scale INSAR by means of high coherence features. In *Third ERS Symposium—Space at the Service of our Environment, Florence, Italy, 17–21 March 1997*, pages 225–228.

Wright, T., Fielding, E., and Parsons, B. (2001). Triggered slip: observations of the 17 August 1999 Izmit (Turkey) earthquake using radar interferometry. *Geophysical Research Letters*, 28(6):1079–1082.

Zebker, H. A., Rosen, P. A., and Hensley, S. (1997). Atmospheric effects in interferometric synthetic aperture radar surface deformation and topographic maps. *Journal of Geophysical Research*, 102(B4):7547–7563.