2. Geodetic network design

Crucial in the traditional geodetic design and analysis of deformation survey networks is the concept of controlled optimization. Meticulous design of the network allows for adjustment and testing procedures that result in sufficient precision and reliability of the estimated parameters, see, e.g. Helmert (1868), Baarda (1968), against acceptable costs. A key but often undervalued requirement in network design is the availability of prior information or assumptions regarding the physics of the deformation process. This information is primarily used to select an optimal parameterization of the problem, in terms of robustness, sensitivity, and a minimal but sufficient number of independent parameters. Once the set of parameters is fixed, they can be related to the precision and characteristics of the various techniques under consideration via an optimally designed network to determine both the internal reliability and the precision and reliability of the estimated parameters.

Practically, the design of the network involves determining the optimal positioning of the benchmarks, in terms of spatial extent and density, and relative positioning within the network. These decisions translate directly in the design matrix of the parameter estimation problem. A non-optimal design may result in rank-deficiencies that hamper the final interpretation of the results. Second, it involves the determination of the minimal repeat frequency of the subsequent campaigns. A sampling rate that is too low will introduce erroneous effects, also known as aliasing, whereas an overestimation of the required sampling rate results in increased costs. Paradoxically, for an optimal design of the network and measurement strategy for deformation monitoring, the deformation needs to be known beforehand.

Main consequences of the network design approach are (i) the necessity of installing artificial benchmarks, (ii) the limitation in spatial benchmark density as a result of practical and financial considerations, (iii) a campaign duration that may be too long with respect to the deformation rate, especially for labor intensive methods such as leveling, (iv) the necessity of a null-survey, used as reference for the deformation measurements. It is evident that deformation that occurred before the null-survey cannot be determined, that deformation processes that have not been anticipated will remain unnoticed, and that deformation processes which are of less importance–in terms of economics, public safety, or science–will not be monitored at all. Local, small-scale deformation will often remain unnoticed, and if a benchmark happens to be in such a local deformation area, it will bias the final results or, in the best case, be rejected as observation.

The dependence on benchmarks poses a significant limitation to the optimization and maintenance of networks. The physical nature of benchmarks, e.g., the bolts for leveling or the pillars for GPS receivers limits the amount of feasible locations. For example, bedrock, or stable (pile-supported) buildings or structural works are needed for leveling benchmarks, while low elevation angle line-of-sights are needed for accurate GPS measurements. Often, these boundary conditions, combined with financial restrictions limit the optimality of the network design. Maintenance of benchmarks is required, but cannot prevent a natural loss of benchmarks in time. For example, a three percent loss of benchmarks per year is quite likely. Over a period of 30 years this results in a loss of 60% of the initial benchmarks.

Using a special application of radar interferometry and under specific conditions, some of the problems listed above can be avoided by using a set of randomly distributed and non-interventive artificial benchmarks. In fact, this is similar to a Monte Carlo approach, where samples are randomly selected from a distribution. Before discussing this methodology we will briefly review the concepts and limitations of conventional radar interferometry for deformation monitoring.

The second group of parameters is influenced by the environment: atmosphere, deformation characteristics, and land surface. Although radar waves are not hindered by clouds, the atmosphere delays the radio waves inhomogeneously, resulting in spatially varying errors in the distance measurements. The degree of disturbance is dependent on climatic conditions and the local weather situation. Weather processes associated with rain, convective clouds, and fronts usually result in a significant error signal, up to several cm's. Since a potential deformation signal is measured relatively between points in the image, a larger distance between points results in an increase in the atmospheric error signal.

Expected deformation characteristics need to be accounted for when considering the feasibility of InSAR. Inaccuracies in the satellite orbit result in large-scale trends and atmospheric signal in smooth phase variability over a wide range of scales. Deformation which has similar characteristics, spatial as well as in magnitude, will be difficult to distinguish from the error signal. For interferometry using only two images, this excludes, e.g. earth tides or slow land subsidence over extended areas. The kinematic characteristics of the deformation play an important role–a sudden deformation associated with an earthquake will be more easy to monitor then tectonic creep, although methodology to measure the latter has been developed as well. Spatial deformation gradients between neighboring pixels need to be less than the radar wavelength.

By far the most important environmental parameter is the reflective surface of the earth. Deriving deformation measures from interferometry is only possible in the case of *coherent* scattering. This implies that for every interferogram, the phase information per pixel should mainly be based on geometry. Therefore, changing reflection characteristics in time, within a resolution cell, should be avoided. This effectively makes water useless for interferometry, since it changes its physical shape within milliseconds. For temporal baselines of several weeks, this often excludes agricultural and heavily vegetated lands as well as areas of human activity such as the construction of buildings or infrastructure. The degree of interferometric correlation between the images is known as *coherence*.

A coherent interferogram results in a smooth fringe-pattern–there is a strong spatial correlation between the modulo- phase values. Areas of low-coherence correspond usually with a noisy fringe pattern. Since the coherence is an important quality measure of the interferogram, varying over the image, it needs to be estimated per pixel. In an ideal situation, repeated measurements under identical conditions would be necessary to estimate the coherence per pixel. However, in the conventional interferometric approach this is impossible because only two images are used to create the interferogram. Thus, there is no redundancy in the interferometric measurements per pixel and its coherence cannot be estimated. Instead, spatial averages within a window centered at the pixel are commonly used, assuming ergodicity. Although this assumption holds in many situations, especially when the terrain characteristics are homogeneous and short temporal baselines are used, it fails in interferograms with spatially varying scattering conditions. Consequently, many interferograms with a long temporal baseline are considerably decorrelated, especially in vegetated regions. Buildings, exposed rocks, or infrastructural works maintain their scattering characteristics over long time intervals and under varying viewing geometries. Recognition of pixels with stable scattering characteristics (both in amplitude and phase) is very difficult, especially when these pixels are isolated amidst decorrelated areas.

4. InSAR permanent scatterers approach

The Permanent Scatterers (PS) technique has been developed to detect isolated coherent pixels and tackle the problem of atmospheric delay errors at the expense of a large number of required images (>30) and a sparse, pixel-by-pixel based evaluation (Ferretti et al, 2000, 2001). Point targets, not affected by temporal decorrelation, are recognized by means of a statistical analysis of their amplitude in all avialable SAR images. The contribution of topography, deformation, and atmosphere can be estimated by carefully exploiting their different time-space behavior. Topography is not dependent of time, but scales linearly with the perpendicular baseline. Deformation is independent of baseline, but is correlated in time. Atmosphere is independent of baseline, uncorrelated in time, but spatially correlated per interferogram.

The combination of all identified permanent scatterers resembles a standard geodetic network, although the positions of the points are found by chance and cannot be optimized. Nonetheless, although the average point density for urban areas is generally between 0.5 and 2.5% of the original number of pixels, this corresponds to 50-400 points per km^2, which is far more than typical leveling or GPS surveys, making optimization less important than in standard geodetic network design. The precision of PS deformation measurements is in the millimeter range, for linear deformation even better than 1 mm/yr. This precision is mainly based on the number of available acquisitions, the temporal and spatial baselines and the Regarding the reliability of this estimate, however, it is based on the assumption, or null-hypothesis, that integer phase ambiguities per pixel in time have been resolved, that the atmospheric signal contribution has been estimated with sufficient precision, and that the deformation signal can be approximated by a 'trend plus signal' zero-order model. The trend, usually a linear approximation, is used to resolve the integer phase ambiguities. This resolution is therefore dependent on a minimum number of acquisitions available and their spatial and temporal distribution. Testing methodologies, to test the model in the null-hypothesis against alternative hypotheses, are currently developed.

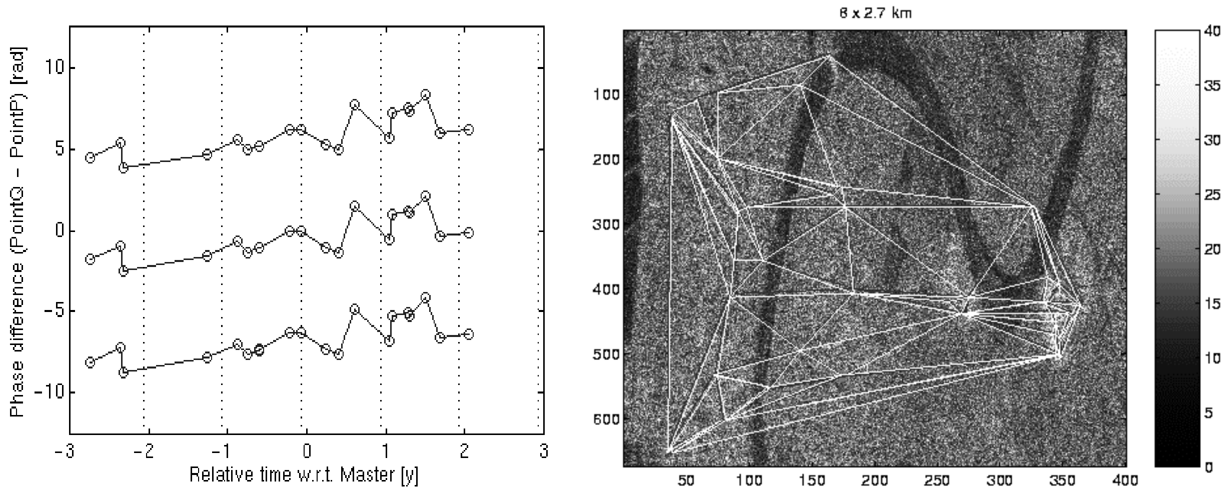

Figure 1 Permanent scatterers example over Hangu, China. A network of opportunity is defined, and the time evolution between two points is shown.

An important characteristic of the method is that it is an opportunistic technique: the exact location of permanent scatterers in an interferometric stack cannot be predicted. This makes it difficult to determine beforehand whether a specific deformation phenomenon, say, the deformation of a specific house, may be monitored. Moreover, the standard application of the technique is subject to the availability of a satellite and a homogeneous acquisition strategy, using comparable swath modes, incidence angles and polarizations. For example, the shift in the center frequency of 5300 MHz to 5331 MHz between the ERS satelites and ENVISAT, equivalent to a 2.3 km baseline, hampers continuation of many permanent scatterers. The successor of ENVISAT is likely to be an L-band mission, which means that a new time series needs to be build up, before PS analysis is possible. Finally, the detection and identification of PS is dependent on rather conservative types of deformation, e.g. linear or seasonal. A isolated coherent target which exhibits a complicated deformation pattern may not be identified.

4.1 Sensitivity

To obtain a general feeling regarding the estimation precision of deformation and topography, we can use a (simplified) model:

$$E\left\{\underbrace{\begin{bmatrix}\varphi_1\\ \vdots \\ \varphi_n\end{bmatrix}}_{y}\right\} = \underbrace{\begin{bmatrix}\alpha t_1 & bB_{\perp,1}\\ \vdots & \vdots \\ \alpha t_n & bB_{\perp,n}\end{bmatrix}}_{A} \underbrace{\begin{bmatrix}\upsilon \\ h\end{bmatrix}}_{x} \qquad (1)$$

where $\alpha = 4\pi\lambda^{-1}$ and $b = 4\pi\lambda^{-1}R^{-1}(\sin\theta)^{-1}$, R is the slant range to the pixel, and θ is the look-angle. The observations are the (unwrapped) phases φ_i for one pixel per interferogram and the unknown parameters are the linear velocity of deformation and the unknown (residual) topographic height of the reflection. Using the null-hypothesis that integer phase ambiguities have been resolved, we can simulate the variance-covariance matrix $Q_{\hat{x}} = (A^T Q_y^{-1} A)^{-1})$ of the unknown parameters for a large number of combinations of t and $B_\perp$, as a function of the number of available acquisitions N. For the variance matrix of the observations we assume uncorrelated observations (per pixel in time). The standard deviation is the sum of the scattering decorrelation plus the atmospheric contributions. For the scattering part we assume a minimum coherence level of 0.9 for the permanent scatterers. For the atmospheric contribution we used a standard deviation of 1.5 cm, which is the maximum observed in interferograms over an area of 50 by 50 km. Figure 3 shows how the precision (standard deviation) of velocity and topography improve with increasing number of acquisitions. Note that both parameters have covariance terms as well. For every number of images N, the values are obtained for 1000 simulations, using a realistic ERS-1/2 acquisition scenario and random baselines. Ten years of data 1992-2002 have been used. It is evident that precisions will decrease if a shorter time span is available. Finally, it needs to be stressed that the hypothesis of correctly resolved integer ambiguities is more likely for a number of images larger than, say, 20 or 30, depending on the acquisition distribution. From the figures we may conclude that linear deformation accuracies can reach standard deviations better than 0.4 mm/yr for deformations and better than 2 m for topography.

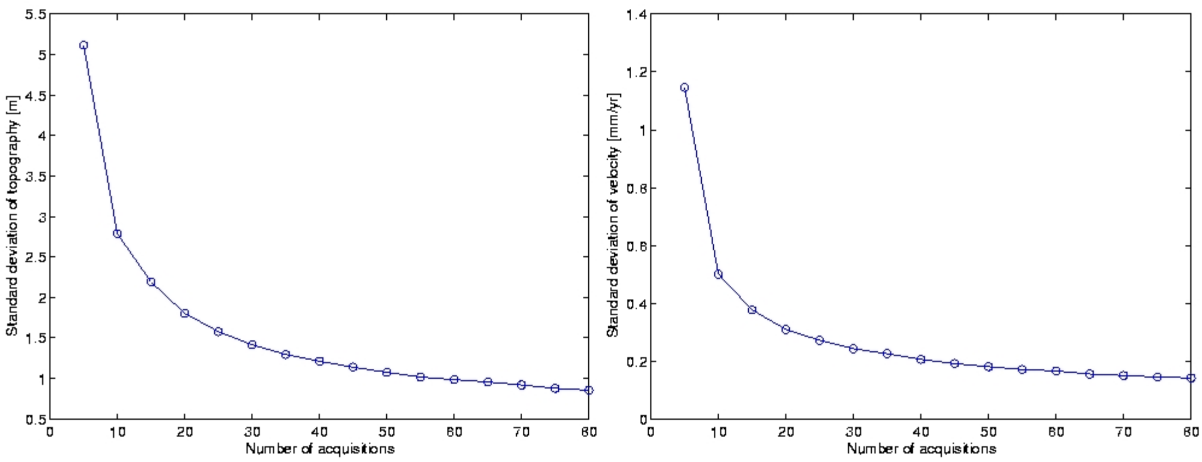

Figure 2 Precision (standard deviation) of estimated deformation and topography as a function of the available images

For every number of images N, the values are obtained for 1000 simulations, using a realistic ERS-1/2 acquisition scenario and random baselines. Ten years of data 1992-2002 have been used. It is evident that precisions will decrease if a shorter time span is available. Finally, it needs to be stressed that the hypothesis of correctly resolved integer ambiguities is more likely for a number of images larger than, say, 20 or 30, depending on the acquisition distribution. From the figures we may conclude that linear deformation accuracies can reach standard deviations better than 0.4 mm/yr for deformations and better than 2 m for topography.

5. Discussion

The feasibility of deformation monitoring using satellite radar interferometry for a specific problem can be quickly evaluated by considering a limited number of parameters. Design parameters, such as the perpendicular and temporal baselines, the radar wavelength, and the number of available images can be obtained from databases which are made available by the space agencies exploiting the satellites. Environmental parameters, such as atmospheric conditions, expected surface deformation and surface decorrelation are often more difficult to predict, and need to be modeled stochastically. Although these factors were previously considered to be limiting factors for the feasibility of deformation monitoring, new developments such as the permanent scatterers technique have broadened the range of applicability. Dedicated InSAR satellite missions are currently proposed to allow for long time series of interferometric data over areas of deformation, e.g. for earthquake, volcano, glacier, and subsidence monitoring.

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