International Journal of Applied Earth Observation
and Geoinformation 6 (2005) 253–260

INTERNATIONAL JOURNAL OF
APPLIED EARTH OBSERVATION
AND GEOINFORMATION

www.elsevier.com/locate/jag

Satellite radar interferometry for deformation monitoring: a priori assessment of feasibility and accuracy

Ramon F. Hanssen

*Delft Institute of Earth-Observation and Space Systems, Delft University of Technology,
Kluyverweg 1, 2629 HS, Delft, The Netherlands*

Accepted 15 October 2004

Abstracts

Conventional satellite repeat-pass radar interferometric measurements can be used for monitoring subsidence phenomena with high accuracies. This methodology was developed for mostly contiguous phase observations, enabling spatial coherence estimation and 2D phase unwrapping. Unfortunately, in many areas in the world, complete temporal decorrelation of the scattering characteristics occurs in a period reaching from days to months. In these circumstances, only urban areas and isolated stable scatterers maintain coherent. The problem is to detect these scatterers amidst their decorrelated neighbors, as spatial coherence estimation is not possible anymore. Methodology for the detection and analysis of such points, labeled permanent scatterers (PS), has been developed by Ferretti et al. [Ferretti, A., Prati, C., Rocca, F., 2000. Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry. IEEE Trans. Geosci. Remote Sens. 38(5), 2202–2212], using many (30 or more) SAR images of a particular site. This approach enables coherence estimation using temporal, pixel-based evaluation. Together, these points form a geodetic *network of opportunity* with different characteristics when compared to traditional geodetic network design.

For practical purposes, it is necessary to define a set of guidelines to assess the feasibility of contiguous or PS radar interferometry for a specific deformation problem. This feasibility is dependent on the number of SAR data acquisitions available, their spatial and temporal baselines and observation statistics, and the expected spatial and temporal behavior of the deformation process. Here, we will discuss the evaluation procedure to assess a priori whether the techniques of contiguous and PS–InSAR are feasible for specific deformation studies in terms of precision and reliability.

Keywords: Satellite radar interferometry; Deformation; Accuracy

1. Introduction

Conventional geodetic deformation measurement techniques have long been used for monitoring various deformation processes, such as land subsidence and seismic deformation. Although various types of fixed instrumentation exist, such as permanently installed tilt, strain, or creep meters, we will refer to campaign-style (non-continuous) network-based surveying methods, such as leveling, (electronic) distance

---

E-mail address: r.f.hanssen@lr.tudelft.nl.

0303-2434/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.jag.2004.10.004

measurements, and triangulation and how these methods mesh with modern space-geodetic methods such as GPS and radar interferometry (InSAR). Main focus is on the concepts of the network design and its implications for final interpretation and quality control. In Section 2, a discussion on geodetic networks is presented, to stress the conceptual differences with the radar interferometric techniques. Recent developments in InSAR have shown that measurements from a limited set of points, known as permanent or persistent scatterers (PS), see Ferretti et al. (2000, 2001), inhomogeneously distributed at unpredictable locations, can be used to obtain high accuracy deformation parameters. We discuss the main parameters that influence the feasibility and accuracy of the conventional (contiguous) InSAR approach in Section 3, and of the PS approach in Section 4.

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), and Teunissen (1990), 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 (minimal detectable bias) 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 which 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 3% 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. As long as sufficient randomly distributed measurements are available, the necessity of network design and optimization is reduced. The parameters determining the feasibility and accuracy of this approach are discussed in Section 4. In the following we will introduce these parameters for the conventional approach.

3. Parameters for conventional approach

The introduction of imaging radar can be regarded as one of the most spectacular developments in remote sensing since the early 1960s. It opened a world of applications in geoscience and astronomy, and provided an alternative to the traditional optical methods of imaging, which need solar illumination and cloudless skies. Imaging radar, obtained using the *synthetic aperture* concept can be used for measuring spatial variations in the distance to the earth, e.g., due to topography, using two radar images and the principle of interferometry (Gabriel and Goldstein, 1988). This technique, known as interferometric synthetic aperture radar (InSAR), applied on board of a satellite, is able to image an area on earth with a typical revisit period of about 1 month. Temporal variations in the satellite-earth distance, due to deformations such as subsidence, earthquakes and volcano dynamics, can be measured as well, with accuracies starting at the sub-cm level. Two main groups of interferometric parameters, the design parameters and the environmental parameters, dictate the potential applications and limitations in deformation monitoring. For a more in-depth review of the technique, see Massonnet and Feigl (1998) or Hanssen (2001) and references therein. Table 1 gives an overview of the most important parameters.

Table 1
Main parameters for feasibility and accuracy analysis

Design parameters	Environmental parameters
Wavelength λ (L,C, X band)	Atmosphere (A)
Baseline ($B_\perp$)	Surface (S)
Temporal baseline (B_T)	Deformation (D)
Number of acquisitions (N)	
Incidence angle, inclination	

The main design parameters are the radar wavelength λ (3–24 cm), the perpendicular baseline $B_\perp$, which is the effective distance between the satellites, the times of the image acquisitions known as the temporal baseline B_T, and the total number of available images N. Note that B_T also contains the information on the repeat interval ΔT and the temporal range of acquisitions, see Table 2. Of course, other parameters such as the incidence angle and the inclination are important as well, but by using different combinations of interferograms their influence can be altered. The environmental parameters are the earth's atmosphere A and surface S, as well as the specific characteristics of the deformation D. Let us discuss these parameters in somewhat more detail.

3.1. Design parameters

The *radar wavelength*, λ, is of major importance. Line-of-sight deformation between two image acquisitions is measured as a fraction of the (semi) wavelength. Depending on the Signal-to-Noise ratio of the radar, the accuracy of the phase measurement maps directly to the accuracy of the deformation. This calls for short wavelengths with high SNR's. However, a short wavelength (3 cm) is scattered by small objects on earth, for example tree leaves. Random movement of these small objects in time disturbs the analysis of the phase signal. Therefore, often a larger wavelength is preferred. A wavelength of 24 cm is reflected more significantly by larger objects, penetrates through foliage, and reflects closer to the ground below trees. Statistically, there is less movement or variation in these larger objects, which limits the disturbance in the

Table 2
List of past and present satellite InSAR missions capable of deformation mapping, mission duration, revisit interval, and wavelength

Mission	Start–end	ΔT (days)	λ (cm)
ERS-1	1991–2000	35(3)	5.6
ERS-2	1995–	35	5.6
ERS-1/ERS-2	1995–1996	1	5.6
JERS	1992–1998	44	23.6
Radarsat	1995–	24	5.6
Envisat	2002–	35	5.6
ALOS	2004–	46	23.6

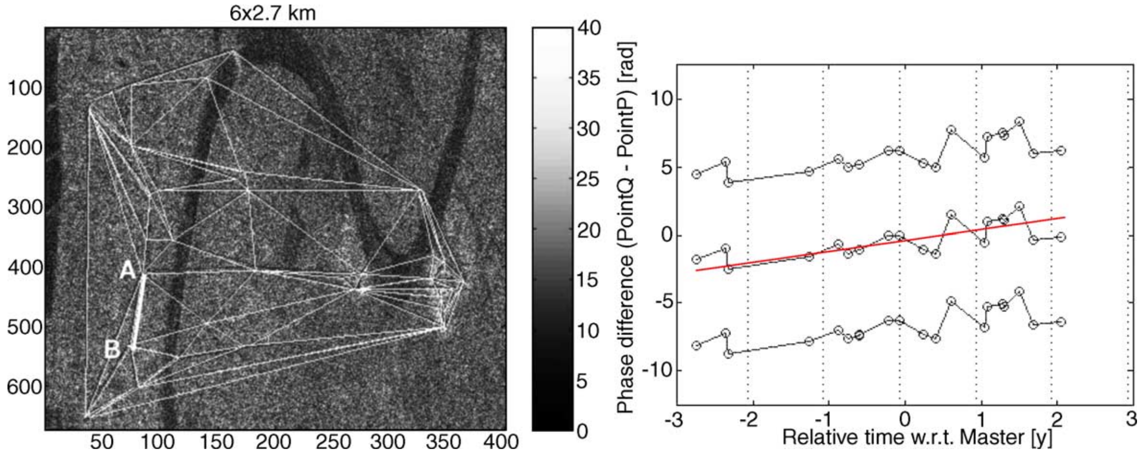

Fig. 1. Permanent scatterers example over Hangu, China. A network of opportunity is defined, and the time evolution between two points is shown.

phase signal analysis. Wavelengths larger than 24 cm will have increased disturbance by the ionosphere and radio interference.

The *perpendicular baseline*, $B_\perp$, introduces the interferometric geometry, see Fig. 1, resulting in sensitivity to topographic height differences. The absolute length varies between 0 (no influence to topographic height) and 1–2 km, (large influence of topographic height) depending on radar wavelength and terrain inclination. Ideally, deformation measurements are performed using a zero-baseline, which excludes all influence of topography. Unfortunately, satellite orbits drift w.r.t. their nominal orbits, resulting in non-zero baselines. External topographic information (DEMs) or high-quality InSAR acquisitions without deformation signal are commonly used for correction of the topographic influence. A second effect of a non-zero baseline is the introduction of phase noise proportional to the baseline length. Due to the baseline length, the imaging geometry varies, changing the radar reflections at the earth's surface. This results in a proportionality between baseline length and phase noise. Note that this holds for the general class of *distributed scattering*, including most natural areas on earth. For the *corner reflector* class of reflections (point scatterers) the baseline restriction is less strict since a wider range of incidence angles will result in a nearly identical reflection. This is one of the main concepts behind the permanent scatterers approach.

The third design parameter is the *temporal baseline*, B_T which is a multiple of the orbit revisit interval ΔT, see Table 2, and dependent of the acquisition planning, subject to the power consumption and possible conflicting scientific or commercial interests regarding the satellite or instrument. The temporal baseline should be long enough to detect the deformation phenomenon of interest. On the other hand noise usually increases considerably proportional with time, for reasons explained below. Apart from the repeat interval, ΔT, we also define the *revisit* interval as the minimum time between two acquisitions over a specific area on earth. Since a position p is imaged from both ascending and descending orbits, as well as between adjacent overlapping tracks, the revisit time can reduce to about a week for ERS/Envisat, even though not all images can be coherently combined. Such an approach yields independent sets of observations over a certain area.

Finally, the total number of acquisitions N is of importance, since the availability of many images allows for alternative ways to recognize high-quality pixels in the image and for optimizing the ratio between the deformation signal and atmospheric error signal.

3.2. Environmental parameters

The second group of parameters are 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 em's over distances longer than 10 km. 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 orbits 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, see e.g., Wright et al. (2001). 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-2π 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 base- line 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. This is discussed in Section 4.

3.3. Synthesis

A generic method for the a priori assessment of the feasibility of conventional InSAR for a specific deformation monitoring problem is based on the evaluation of design and environmental parameters. The expected deformation characteristics are usually the starting point. Especially the magnitude of the deformation, its temporal behavior and its spatial gradients and extent are main factors influencing this feasibility. Inspection of the surface characteristics (vegetation) can help to estimate the amount of decorrelated areas in the image. Atmospheric conditions are hard to determine a priori, but in relation to the deformation characteristics even rough estimates of atmospheric signal can give a first indication of the signal (deformation) to noise (atmosphere) ratio. Finally, design parameters such as image availability of the potential sensors should be checked, as well as perpendicular and temporal baseline characteristics.

4. Parameters for permanent scatterers approach

The 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 available 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 linearly correlated with the perpendicular baseline length and spatially correlated dependent on terrain roughness. Deformation is independent of baseline, but correlated in time and space. Atmosphere is independent of baseline, uncorrelated over time intervals of one day or more, but spatially correlated per interferogram (Hanssen, 2001).

The combination of all identified permanent scatterers resembles a standard geodetic network, see the example distribution in Fig. 1, although it is in fact a network of opportunity; 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 main design parameters influencing the feasibility and accuracy of PS–InSAR are the number of acquisitions, N, and the temporal and spatial baselines, B_T and $B_\perp$. Of the environmental parameters, the influence of the atmosphere is now significantly reduced due to the possibility of filtering the temporally uncorrelated atmospheric signal. Also, the influence of the surface in terms of decorrelation is reduced, since only time-coherent targets are used in the PS–InSAR approach. An additional parameter that needs to be introduced is the autonomous movement of a scatterer, $-D_{\text{aut}}$, defined as deformation of a scatterer which is uncorrelated to both neighboring scatterer, uncorrelated to the deformation signal of interest, but correlated in time. Autonomous movement can be the due to the unstable foundation of a building, multipath reflections showing very localized ground subsidence, temperature effects on constructions, etc.

The most important feature of the method is its opportunistic nature: 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 an object, may be monitored. On the other hand, experience shows that many urbanized areas have a high density of useful PS, and spatially correlated deformation signals will therefore be sufficiently sampled. 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 5300–5331 MHz between the ERS satellites and ENVISAT, equivalent to a 2.3 km baseline, makes continuation of many permanent scatterers difficult, but not impossible. If the successor of ENVISAT will be an L-band mission, this means that a new time series needs to be build up, before PS analysis is possible. Finally, in practice 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. Precision and reliability

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

$$E\left\{\underbrace{\begin{bmatrix}\varphi_1\\ \vdots\\ \varphi_n\end{bmatrix}}_{y}\right\} = \underbrace{\begin{bmatrix}a_1 & b_1\\ \vdots & \vdots\\ a_n & b_n\end{bmatrix}}_{A}\underbrace{\begin{bmatrix}v\\ h\end{bmatrix}}_{x} \qquad (1)$$

where $a_i = 4\pi\lambda^{-1} B_{T,i}$, $b_i = 4\pi\lambda^{-1} R^{-1}(\sin\theta)^{-1} B_{\perp,i}$, R is the slant range to the pixel and θ the look-angle. The observations are the (unwrapped) phases φ_i for 1 pixel per interferogram and the unknown parameters are the linear velocity of deformation and the unknown (residual) topographic height of the reflection. The simplification is that unwrapped data are assumed and orbital and atmospheric trends are neglected. Using the null-hypothesis that integer phase ambiguities have been resolved, we can determine the variance-covariance matrix $Q_{\hat{x}} = (A^{\mathrm{T}} Q_y^{-1} A)^{-1}$ of the unknown parameters for a given number of combinations of $B_{\mathrm{T},i}$ and $B_{\perp,i}$, 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 use a standard deviation of 1.5 cm, which is the maximum observed in interferograms over an area of 50 km × 50 km. Usually this influence has been filtered out significantly in the processing. Fig. 2 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 from 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/year for deformations and better than 2 m for topography.

The internal reliability, or minimal detectable bias, is defined as the size of a model error that can be detected with a certain probability, e.g., 80%. This is mainly influenced by the assumptions, or null-hypothesis, that: (i) integer phase ambiguities per pixel in time have been resolved, (ii) the atmospheric signal contribution has been estimated with sufficient precision, and (iii) the deformation signal can be approximated by a ‘trend plus signal’ zero-order model. The trend, often a linear approximation, is used to resolve the integer phase ambiguities. Ambiguity resolution is therefore dependent on a minimum number of acquisitions available and their spatial and temporal distribution, N, $B_{\perp}$ and B_{T}, respectively. Testing methodologies, to test the model in the null-hypothesis against alternative hypotheses, are currently developed (Kampes and Hanssen, 2004).

The external reliability is defined as the influence that an undetected model error will have on the final adjustment results. The main problem here is that autonomous movement, Daut, that is not incorporated in the model results in a model error. As a result,

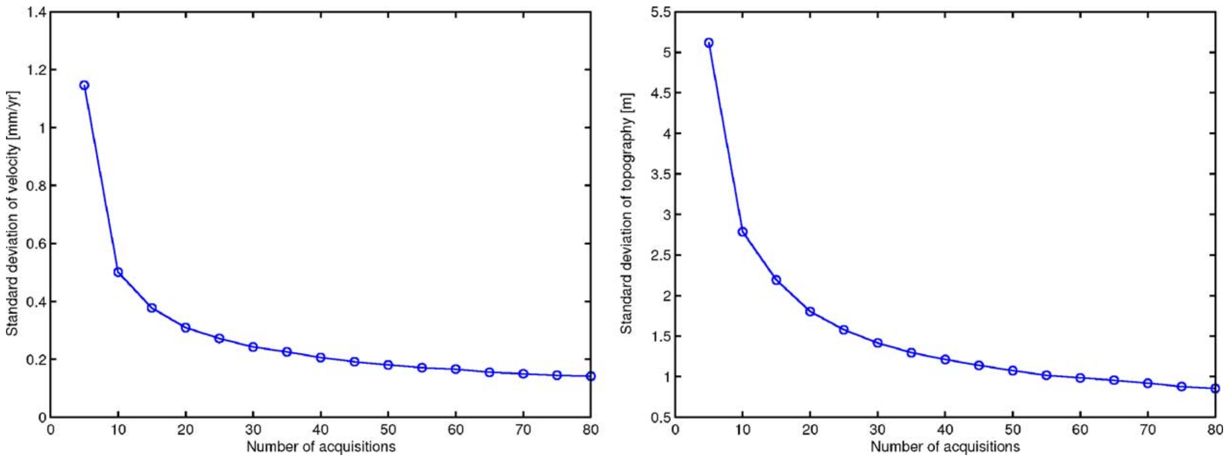

Fig. 2. Precision (standard deviation) of estimated deformation and topography as a function of the available images.

attributing the estimated parameters directly to a physical subsidence mechanism is not straightforward.

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 mission designs are currently under consideration to allow for long time series of interferometric data over areas of deformation, e.g., for earthquake, volcano, glacier, and subsidence monitoring.

References

Baarda, W., 1968. A Testing Procedure for Use in Geodetic Networks, vol. 5 of Publications on Geodesy, second ed. The Netherlands Geodetic Commission, Delft.

Ferretti, A., Prati, C., Rocca, F., 2000. Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry. IEEE Trans. Geosci. Remote Sens. 38 (5), 2202–2212.

Ferretti, A., Prati, C., Rocca, F., 2001. Permanent scatterers in SAR interferometry. IEEE Trans. Geosci. Remote Sens. 39 (l), 8–20.

Gabriel, A.K., Goldstein, R.M., 1988. Crossed orbit interferometry: theory and experimental results from SIR-B. Int. J. Remote Sens. 9 (5), 857–872.

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

Helmert, F.R., 1868. Studien Uber rationelle Vermessungen im Gebiete der höheren Geodäsie. Zeitschrift fur Mathematik und Physik 13, 73.

Kampes, B.M., Hanssen, R.F., 2004. Ambiguity resolution for permanent scatterer interferometry. IEEE Trans. Geosci. Remote Sens. 42 (11), 2446–2453.

Massonnet, D., Feigl, K.L., 1998. Radar interferometry and its application to changes in the earth's surface. Rev. Geophys. 36 (4), 441–500.

Teunissen, P.J.G., 1990. Quality control in integrated navigation systems. IEEE Aerospace Electron. Syst. Mag. 5 (7), 35–41.

Wright, T., Parsons, B., Fielding, E., 2001. Measurement of interseismic strain accumulation across the North Anatolian Fault by satellite radar interferometry. Geophys. Res. Lett. 28 (10), 2117–2120.