Design Parameters and Environmental Factors Affecting Feasibility

Deformation Monitoring by Satellite Interferometry

The introduction of imaging radar has been a very important development in remote sensing since the early 1960s. It has opened up many new applications in geoscience and astronomy and provides an alternative to optical imaging, which needs solar illumination and cloudless skies. Imaging radar may be employed for measuring spatial variations in the distance to the earth, for example those caused by relief, using two images obtained by Interferometric Synthetic Aperture Radar (InSAR). The feasibility of deformation monitoring by InSAR may be quickly evaluated by considering a limited number of design parameters and environmental factors. The authors treat these parameters and factors in greater detail.

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InSAR applied on board of a satellite is able to image, with a one month revisit period, any given area on earth. Temporal variations in the satellite-earth distance due to deformations such as subsidence, earthquakes and volcanoes may also be measured, with accuracy starting at the sub-cm level.

When is InSAR feasible for a particular project on deformation monitoring? This depends on two main groups of parameters (Figure 1):

- design parameters, mainly consisting of radar wavelength λ (3-24 cm), perpendicular baseline $B_\perp$ (effective distance between the satellites), temporal baseline B_T, , which is the time interval between the image acquisitions, and the total number of images
- environmental factors, consisting of earth's atmosphere *A*, the characteristics of the deformation *D*, and the surface *S*

Radar Wavelength

The Line-Of-Sight (LOS) deformation between two images is measured as a fraction of the (semi) wavelength. Depending on the Signal-to-Noise Ratio (SNR), the accuracy of the phase measurement directly affects the accuracy of the deformation. This calls for short wavelengths with high SNRs. However, a short wavelength (3 cm) is reflected by small objects like tree leaves. In fact, the radar return is the sum of the contributions of all the small objects within the resolution cell.

Return is sum of contributions of all small objects within the resolution cell

Random movements of small objects disturb 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 beneath trees. Statistically, there is less movement or variation in these larger objects, which limits disturbance in the phase signal analysis. Wavelengths larger than 24 cm will

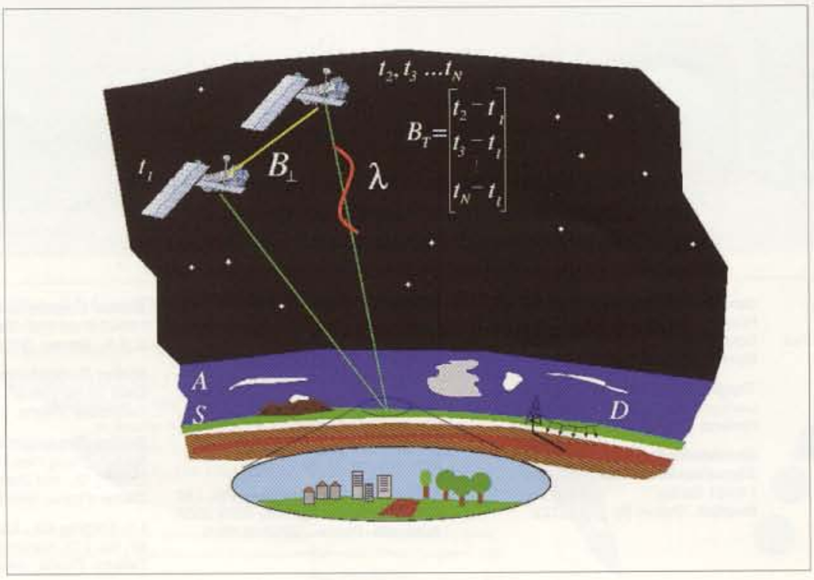

Figure 1, Main parameters affecting the feasibility of deformation monitoring using satellite radar interferometry

Radar

Mission	Start-End	Revisit Interval (days)	Wavelength (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

Table 1. List of past and present InSAR missions capable of deformation monitoring

have disturbance increased by the ionosphere and radio interference.

Baselines

The perpendicular baseline, $B_\perp$, introduces the interferometric geometry resulting in sensitivity to topographic height differences. The absolute length varies between 0 (no influence on topographic height) and 1-2 km (large influence on topographic height) depending on the radar wavelength and terrain inclination. Ideally, deformation measurements are performed using a zero-baseline, which excludes all influence of topography. Unfortunately, satellite orbits drift with respect to their nominal orbits, resulting in non-zero baselines. External topographic information (DEMs) or high-quality InSAR images 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 increasing with the baseline length.

The temporal baseline, B_T, is a multiple of the orbit revisit interval (Table 1) and depends on acquisition planning, subject to power consumption and possible conflicting scientific or commercial interests regarding the satellite or instrument. The temporal baseline should be long enough to detect deformation phenomenon of interest. On the other hand, noise usually increases considerably proportional to time.

Rain, clouds and fronts result in error up to several centimetres

Many images allow for alternative ways of recognising high-quality pixels in the image and for optimising the ratio between the deformation signal and atmospheric error signal.

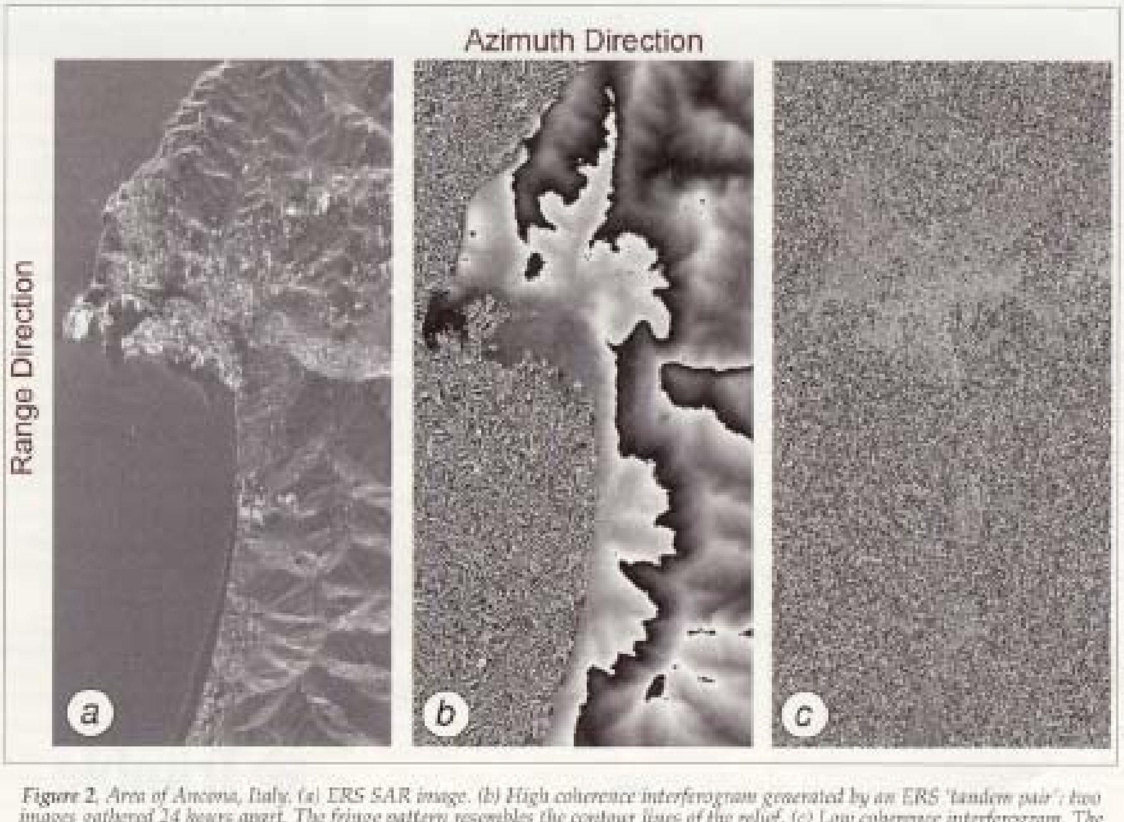

Figure 2. Area of Ancona, Italy. (a) ERS SAR image. (b) High coherence interferogram generated by an ERS 'tandem pair': two images gathered 24 hours apart. The fringe pattern resembles the contour lines of the relief. (c) Low coherence interferogram. The perpendicular baseline is small (smaller than 20 metre) but the temporal baseline is more than one year

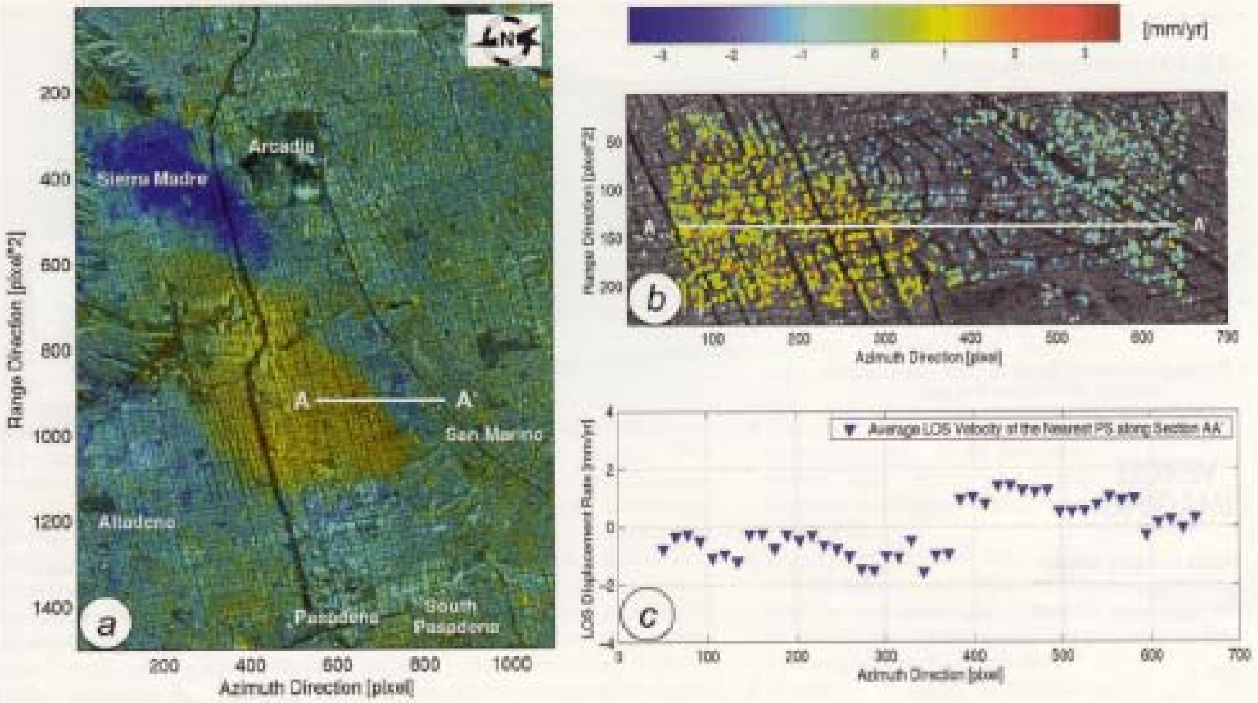

Figure 3. Permanent Scatterers (PS) technique applied to radar images of Raymond Fault, CA, USA. For explanation see paragraph 'Example'

Atmosphere

Although radar waves are not hindered by clouds, the atmosphere delays radio waves non-homogeneously, resulting in spatially varying errors in distance measurements. The degree of disturbance depends on climatic conditions and the local weather situation. Weather processes associated with rain, convective clouds and fronts usually result in a significant signal error, up to several centimetres. 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.

Deformation Characteristics

Inaccuracies in 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 signal error. For interferometry using only two images this excludes, for example, earth tides or slow land subsidence over extended areas. Kinematic characteristics of deformation play an important role - a sudden deformation associated with an earthquake will be more easy to monitor than tectonic creep, although a methodology to measure the latter has also been developed. Spatial deformation gradients between neighbouring pixels need to be less than the radar wavelength.

Surface Reflections

By far the most important environmental parameter is the reflective surface. Deformation measures can only be derived in the case of coherent scattering. (The degree of interferometric correlation between the images is known as coherence.) This implies that for every interferogram the phase information per pixel should mainly be based on geometry. As a result, interferometric measurements cannot be carried out when the local reflectivity of the terrain changes in time. Changing reflection characteristics over time within a resolution cell should, therefore, be avoided. This effectively makes water useless for interferometry, since it changes its physical shape within milliseconds. For temporal baselines of several weeks, this same factor also often excludes agricultural and heavily vegetated lands, as well as areas of human activity such as construction works. A coherent interferogram results in a smooth fringe-pattern (Figure 2B). Areas of low-coherence correspond to a noisy fringe pattern (Figure 2C). Since the coherence is an important quality measure, it needs to be estimated per pixel. For this, repeated measurements under identical conditions are principally needed. However, in the

> *Measurements cannot be carried out when reflectivity of the terrain changes in time*

conventional approach this is impossible because only two images are used, resulting in no redundancy. Spatial averages within a window centred at the pixel are therefore commonly used, assuming ergodicity. Although this assumption holds in many situations, especially when the terrain characteristics are homogeneous and short temporal baselines are used (Figure 2B), it fails in interferograms with spatially varying scattering conditions. Consequently, many interferograms with a long temporal baseline are considerably decorrelated, especially in vegetated regions (Figure 2C). Buildings, rocks or infrastructural works maintain their scattering characteristics over long time periods 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.

> *Recognition of pixels with stable scattering characteristics is very hard*

Permanent Scatterers

The design parameters under discussion may be obtained from databases made available by the space agencies exploiting satellites. Environmental parameters are often more difficult to predict and need to be modelled stochastically. Although these factors were previously considered to be limiting factors, new developments such as the Permanent Scatterers (PS) technique have broadened the range of applicability.

PS was developed to detect isolated coherent targets and to tackle the problem of atmospheric delay errors at the expense of many images (over twenty) and a sparse, pixel-by-pixel based evaluation. Point targets, which are not affected by temporal changes, are recognised by a statistical analysis of their amplitude in all SAR images (Figure 3). The contribution of topography and atmosphere may be estimated and removed by carefully exploiting their different time-space behaviour. This increases the measurement accuracy from centimetre to millimetre level. The combination of all permanent scatterers resembles a standard geodetic network, although the positions of the points are found by chance and cannot be optimised. 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 50-300 points per kilometre - far more than typical levelling or GPS surveys - making optimisation less important than it is in standard geodetic network design. The accuracy of PS deformation measurements lies in the millimetre range, for linear deformation even higher than 0.1 millimetre per year. The high repeat rate of new acquisitions leads to a timely identification of changing deformation characteristics. This is important, for example, in monitoring the stability of individual buildings.

Example

An example of the results that can be achieved by means of the PS technique is shown in Figure 3. Figure 3a shows the LOS velocity field across Raymond Fault in California, estimated from 55 ERS acquisitions. The PS density is very high (more than 200 PS/km^2), so that the estimated LOS velocity field looks continuous. The estimated accuracy of the velocity values is better than 0.5 millimetre per year. Figure 3b shows a close-up on cross section AA'. Here location and velocity of the PS (colour-coded) have been highlighted and their density may be better appreciated. Figure 3c shows LOS displacement rates relative to the PS along section AA'. The stepwise discontinuity of about 2 millimetre per year may be easily identified and the hanging wall of the fault can be located with an accuracy of a few tens of metres.

Future

Dedicated InSAR satellite missions are currently proposed to allow for long time series of interferometric data over areas of deformation, for example for earthquake, volcano, glacier and subsidence monitoring.

Further Reading

- 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. and Goldstein, R.M. (1988), Crossed orbit interferometry: theory and experimental results from SIR-B, Int.J. Remote Sensing, 9(5):857-872
- Hanssen, R.F. (2001), Radar Interferometry: Data Interpretation and Error Analysis, Kluwer Academic Publishers, Dordrecht
- Massonnet, D. and Feigl, K.L. (1998), Radar interferometry and its application to changes in the earth's surface, Reviews of Geophysics, 36(4):441-500
- Rosen, P., Hensley, S., Joughin, I.R., Li, F.K., Madsen, S., Rodriguez, E. and Goldstein, R. (2000), Synthetic Aperture Radar Interferometry, Proceedings of the IEEE, 88(3):333-382◆

Biography of the Authors

Dr. Ramon Hanssen received an MSc degree in geodesy in 1993 and a PhD degree in 2000, both from the Delft University of Technology, where he is currently assistant-professor in geostatistics, remote sensing and radar. Between 1995 and 2000 he carried out research in the field of InSAR at the Delft University of Technology, Stanford University, the German Aerospace Center, Stuttgart University, and Scripps Institution of Oceanography.

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