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Detecting site instability hazards with SAR interferometry

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ABSTRACT: The advanced multi-temporal Differential Synthetic Aperture Radar Interferometry (DInSAR) methods e.g. Permanent Scatterers Interferometry (PSInSAR), mitigate the limitations of conventional DInSAR and extend the applicability of radar interferometry from wide-area, regional-scale detection and monitoring of ground surface deformations to local-scale engineering geology investigations of site instability linked to settlements and/or deterioration of engineering structures. Since the presence of movements can be taken as a direct evidence of potential failure hazard, PSInSAR can be used to provide a preliminary distinction of conditions of relative stability or instability. Furthermore, thanks to a regular re-visit schedule of the radar satellites and the millimetric precision of measurements, a long-term monitoring of small displacements is feasible. To show the practical applicability of PSInSAR in site instability investigations we present two examples from Italy's capital, which reveal (i) presence of local subsidence (settlements) in areas of the old Rome underlain by the Holocene age alluvial deposits of the Tiber River and (ii) very local site instability (or monument deterioration) in the Imperial Forum area (ancient Rome).

1 INTRODUCTION

River valleys and alluvial plains are among the environments that in the last centuries have suffered major man-made modifications. This has often resulted in an increase in ground failure hazards, also in areas historically known to be geomorphologically stable. It follows that the evidence of past or even recent conditions of stability may not be reliably used to assess the current levels of potential hazards and that often more site-specific information is needed for adequate hazard analyses. In situ investigations and monitoring, however, are expensive, time consuming, and thus unfeasible on a regional scale.

In this context the space-borne DInSAR techniques are attractive because of their capability to provide wide-area coverage (thousands km2) and, under suitable conditions, spatially dense information on small ground surface deformations (e.g. Gabriel *et al.* 1989; CEOS DMSP Report 2002; IGOS GEOHAZARDS 2004; Wasowski *et al.* 2004). Furthermore, the advanced multi-temporal DInSAR methods such as the Permanent Scatterers Interferometry (PSInSAR; Ferretti *et al.* 2000, 2001) and Small

Baseline Subset (SBAS; Lanari *et al.* 2004) overcome the limitations of conventional DInSAR and extend the applicability of radar interferometry from regional to local-scale engineering geology investigations of ground instability.

To foster the awareness of the utility of radar-based remote sensing, this work presents some examples of PSInSAR applications to site instability problems in Rome, Italy. Practical aspects of radar interferometry are stressed (advantages, limitations, output products). The importance of ground truth is also considered, because the results from advanced pixel by pixel DInSAR processing reflect performance of targets, whose actual displacements may arise from a variety of causes (e.g. natural subsidence, sub-surface civil engineering, mining and fluid extraction, engineering structure deterioration, expansion/shrinkage of soils).

2 SATELLITE RADAR INTERFEROMETRY AND THE PS TECHNIQUE

2.1 *Background*

Here we provide only a short introduction to space-borne SAR interferometry. For details the reader is referred to remote sensing literature (e.g. Hanssen 2001).

The basic principle of interferometry relies on the fact that the phase of SAR images is a modulo-2π measure of the sensor-target distance. Distance variations are determined by computing, on a pixel by pixel basis, the phase difference relative to two SAR images acquired over the same area. The SAR phase data can be further exploited by removing the topographic contribution from the interferometric phase; this involves the generation and subtraction of the so-called synthetic interferogram and forms the basis of Differential SAR Interferometry – DInSAR. This technique has the wide-area (thousands of km^2) potential to detect millimetric target displacements along the radar Line-Of-Sight (LOS) direction. The DInSAR applications are possible as long as the phase contribution generated by the electromagnetic scattering on the Earth surface within the area of interest remains nearly constant (so-called coherence condition) between the two radar acquisitions involved in each interferogram.

The loss of coherence, typically related to the presence of vegetation cover, represents a major limitation of the conventional DInSAR, in particular in the case of applications that require long-term (months-years) observations. Another serious drawback is related to the presence of atmospheric distortions affecting the interferometric phase.

2.2 *Permanent scatterer interferometry* (*PSInSAR*)

The limitations of the conventional DInSAR can be mitigated by using PSInSAR technique. For a comprehensive description of PSInSAR and validation tests the reader is referred to Ferretti *et al.* (2000, 2001) and Colesanti *et al.* (2003a,b). In short, the PSInSAR technique takes advantage of long temporal series of SAR data of an area, acquired by the satellite on the same orbit, to filter out atmospheric artefacts. It does so by generating multiple differential interferograms from a set of radar scenes and subjecting them to numerical and statistical analyses in order to identify a sub-set of image pixels on which high precision measurements can be performed. These pixels, virtually unaffected by temporal and geometrical decorrelation, are called Permanent Scatterers (PS). PS targets correspond mainly to man-made objects such as monuments, lamp standards, antenna and other metallic structures on the roofs of buildings, and secondarily to natural objects such as rock outcrops. It is also possible to use specially fabricated reflectors.

For each PS the analysis generates the following output products:

1. Geocoded position (accuracy of latitude/longitude estimate typically better than 5 m) and high precision estimate of the elevation (standard deviation around 1 m);
2. Time series of the displacement occurring along the sensor-target LOS direction. The precision of a single LOS measurement ranges from 1 to 3 mm, whereas average PS movement velocities can be determined with submillimetric precision (typically within 0.5 mm/yr). With the current sensors, however, only the projection of a displacement along LOS is possible and this can represent a significant limitation for the applications that require 3D displacement data. For example for the European Space Agency (ESA) ERS-1/2 satellites the LOS direction is close to the vertical (average incidence angle on flat Earth surface is about 23°).

As in the case of the conventional DInSAR, displacement information is relative both temporally and spatially. In time all data are referred to the so-called master image, common to the entire series of interferograms and in space the data are referred to a reference PS located on a stable site.

Finally, with the present (as of 2006) C-band SAR data (5.66 cm wavelength) and the satellite repeat-cycle of 35 days for the ESA sensors and 24 days for the Canadian RADARSAT, PSInSAR allows monitoring of only slow ground surface movements (on the order of few cm/yr). This and other limitations will be overcome in the near future thanks to the new space-borne radar sensors (e.g. ALOS-PALSAR, RADARSAT-2) and radar satellite constellations (e.g. Cosmo-Sky-Med).

3 APPLICATIONS OF PSINSAR TO SITE INSTABILITY PROBLEMS

3.1 *General*

With the current technical characteristics of space-borne radar sensors, PSInSAR is ideally suited for monitoring low velocity (sub)vertical motions of flat or gently inclined areas of the Earth surface. Indeed, there are many successful case studies illustrating the great potential of PSInSAR or similar advanced multi-temporal DInSAR techniques applied to investigate geological or man-induced ground surface deformations involving mainly downward or upward movements (e.g. Ferretti *et al.* 2000; Colesanti *et al.* 2003a,b; Ferretti *et al.* 2004; Hilley *et al.* 2004; Lanari *et al.* 2004; Colesanti *et al.* 2005). Furthermore, thanks to wide-area coverage of radar sensors, combined with the high spatial resolution of the PSInSAR products, the technique can be profitably applied to investigate hazards from both large-scale (e.g. large river valley and alluvial plain subsidence) and small-scale processes (e.g. local subsidence related to mining or other subsurface engineering works, fluid or gas extraction).

Below we provide examples of local scale displacements detected via PSInSAR technique in Rome, Italy. The PS motion data point to what can be generally called site instability. We use this term because the downward displacements of the PS, which correspond mainly to buildings, probably reflect the interactions of different local phenomena such as land subsidence linked to compaction of sediments (settlements), lowering of groundwater levels, as well as deterioration of engineering structure.

3.2 *Examples of site instabilities detected in Rome*

The applications of the PSInSAR technique are especially rewarding in cases of large urbanised areas where coherence conditions are typically very good and PS density is greater than 100 PS/km^2 (Ferretti *et al.* 2006). This is also the case of Rome, Italy, for which more than 100 ERS images covering the time span of 1992–2000 were exploited for PSInSAR analysis.

The first example of site instability detected in Italy's capital regards the part of the old city. The PS data show the occurrence of very slow downward displacements (within 10 mm/yr) in the area extending from the Vatican across the Tiber River (Fig. 1). The Vatican area, which occupies one of the Rome's seven hills (up to few tens of metres above the river level), results to be motionless. This outcome is not surprising

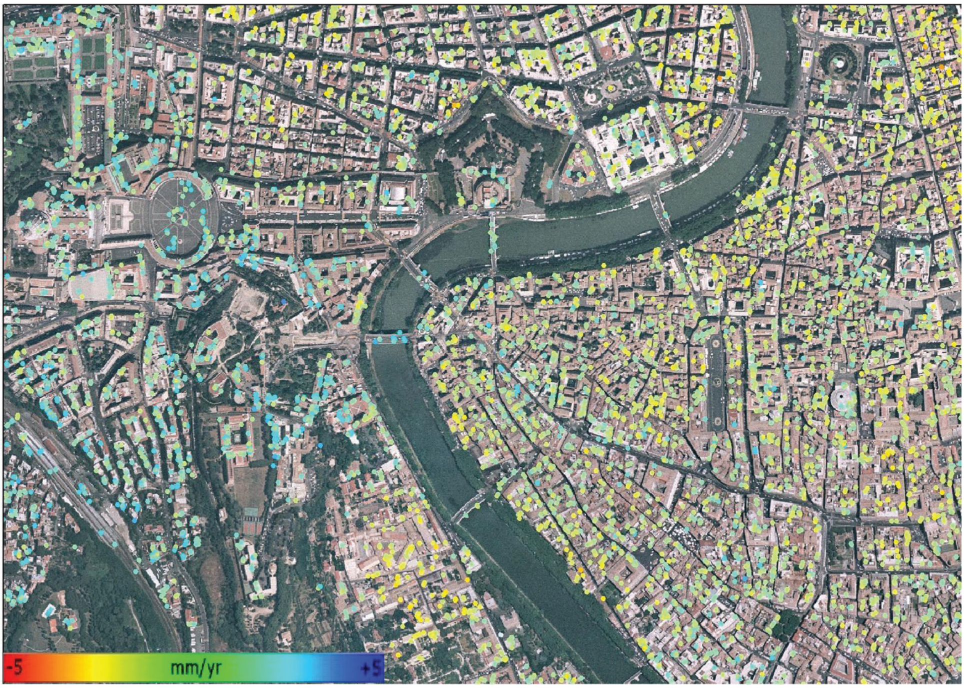

Figure 1. Results of Permanent Scatterers Interferometry (PSInSAR) showing very slow downward displacements in the old Rome area extending from the Vatican (upper left of the image) across the Tiber River. Dots correspond to PS whose colours depend on the Line Of Sight (LOS) value in mm/yr (for visualisation purposes the velocities are saturated to ± 5 mm/yr). The background image is an aerial orthophoto of the city.

considering the differences in surface geology between the Vatican and the Tiber River area. The former is characterised by the presence of older and relatively competent lithological units (Pliocene sedimentary rocks and Pleistocene volcanics), whereas the latter includes mainly younger age (Holocene) alluvial deposits (Ventriglia, 2002) that are more compressible. Thus the downward movements in the old city near the Tiber River can be attributed to local subsidence phenomena (geotechnical settlements), in relation to the presence of geological materials susceptible to loading. The displacements may also reflect local subsidence linked to groundwater level variations.

The second example regards the ancient Rome area including famous ruins and monuments of the Roman Empire such as the Forum, Palatine and Colosseum (Fig. 2). In general PSInSAR analysis reveals the lack of significant ground surface deformations in the area. The exception is a group of few downward moving PS, located in the central part of the Forum, just north of the Palatine hill (Fig. 2). These PS point to what appears to be a very local site instability problem. The movements can be related to structural deterioration of the ancient remains or to a site-specific ground settlement phenomenon at the base of the Palatine hill, or to both. The surface geology of the site is characterised by the presence of the old (Early Pleistocene) alluvial deposits of the Paleo-Tiber River (Ventriglia, 2002).

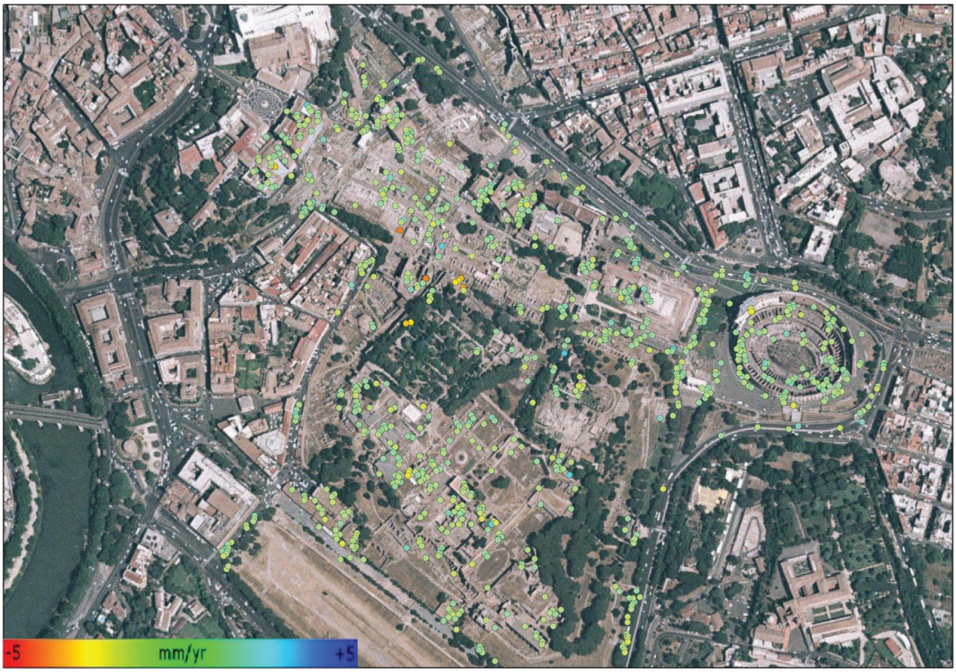

Figure 2. Results of Permanent Scatterers Interferometry (PSInSAR) showing a small cluster of downward moving PS, located in the central part of the Roman Forum, just north of the Palatine hill (note Colosseum to the right). Dots correspond to PS whose colour depends on the Line Of Sight (LOS) value in mm/yr. The background image is an aerial orthophoto of the city.

The above examples demonstrate the capability of PSInSAR technique to detect instability on a site specific or individual building scale. This can be particularly important for the protection of man-made structures and ancient monuments in areas perceived to be unaffected by ground deformations.

4 CONCLUDING REMARKS

The practical benefits of regular space-based monitoring of densely populated centres have been clearly recognised by IGOS GEOHAZARDS (2004) and similar initiatives (e.g. ESA Terrafirma project). The PSInSAR technique is particularly suitable for investigating geohazards in urbanised areas thanks to the capability to provide rapidly information on the Earth's surface deformations at both:

– The wide-area level, needed for a general reconnaissance of the region of interest;
– The site specific level, needed to assess individually the stability of each site.

The availability of information at both wide-area and site specific level facilitates the interpretation of site conditions and can be essential for a correct assessment of potential future hazards. Furthermore, the data on the temporal evolution of deformations, and in particular on movement rates (and amounts) can be of great value for the assessments of severity of potential ground failures.

Although the information provided by the PSInSAR technique is rather simple (changes in LOS distance between a radar sensor and coherent targets), and the moving PS can be taken as direct indicators of potential site instability, the interpretation of the exact significance of the registered displacements and the identification of the main causative mechanism can be challenging. This may be particularly true when dealing with very low magnitude displacements in urban centres situated in tectonically or volcanically active settings. There the movements can arise from an interplay of different natural and anthropogenic processes and may thus reflect complex deformation mechanisms. It follows that before the PSInSAR results can be confidently used for hazard/risk zonation purposes, they should be suitably integrated with in situ data, paying much attention to the geotechnical setting of the area of interest and to the structural behaviour of man-made objects that act as PS targets.

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