Satellite interferometry for monitoring ground deformations in the urban environment

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Abstract: Satellite differential synthetic aperture radar interferometry (DInSAR) is an attractive technique for detecting and monitoring ground surface deformations arising from regional scale processes (e.g. seismic/volcanic). The technique, however, is not effective for site-specific evaluations, because of coarse resolution and coherence loss limitations. Permanent Scatterers interferometry (PSInSAR), developed at Politecnico di Milano and improved at T.R.E. s.r.l. company, overcomes the limitations of DInSAR and extends the applicability of radar interferometry to local-scale geotechnical investigations of slope instability and soil settlement/ground subsidence. The PSInSAR analysis allows the identification of numerous radar targets (the PS) where very precise displacement information can be obtained. Considering the regular re-visit time and wide-area coverage of satellite radar sensors, and that PS usually correspond to buildings and other man-made structures, this technique is particularly suitable for applications in urban environments, which often represent a harsh setting for GPS or conventional topographic surveying.

To demonstrate the effectiveness of PSInSAR in monitoring urban ground deformations we present examples of practical applications in Italy, Japan, and US.

PS data can assist in:

- Identification and delineation of areas affected by slow deformations.
- Estimation of surface velocity and acceleration fields with millimetric precision.
- Identification of the source of ground instability by analysing in situ and multi-temporal remotely sensed data.

The regular monitoring from space of urban areas offers a unique possibility for detecting precursory deformations associated with the initiation of ground instability, a key element for early warning and hazard mitigation in highly populated areas. Satellite data has to be well ground truthed, because they reflect performance of targets, whose actual or apparent displacements may arise from a variety of causes (e.g. seismic, tectonic or volcanic deformation, slope movement, fill settlement, subsurface civil engineering, mining and fluid extraction, structure deterioration, expansion/shrinkage of soils).

Résumé: L'interférométrie différentielle radar (DInSAR) est une technique attrayante pour détecter et surveiller les déformations du sol résultant de processus à l'échelle régionale (par exemple dû à un séisme/volcan). Cependant, cette technique n'est pas efficace pour évaluer un site spécifique en particulier, en raison de la résolution spatiale et des limitations dues à la perte de cohérence. La technique d'interférométrie par poins stables (PSInSAR), développée chez Politecnico di Milano et améliorée par la société T.R.E.s.r.l., surmonte les limitations de DInSAR et permet d'appliquer localement les techniques d'interférométrie radar pour notamment faire des mesures géotechniques sur l'instabilité de pente et l'affaissement ou susidence du sol. L'analyse PSInSAR permet l'identification de nombreuses cibles radar (les diffuseurs permanents ou « PS ») pour lesquels une estimation très précise du déplacement peut être obtenue. Etant donnés les atouts fréquence régulière de passage et la large couverture des satellites radar, et étant donné que les PS correspondent habituellement aux bâtiments et d'autres constructions, cette technique est particulièrement appropriée aux applications dans les environnements urbains, qui représentent souvent un mise au point difficile pour les GPS ou pour les mesures topographiques conventionnelles.

Pour démontrer l'efficacité de la technique PSInSAR pour surveiller des déformations urbaines du sol, nous présentons des exemples d'applications en l'Italie et au Japon. Les données de PS peuvent aider à :

- l'identification et la délimitation des secteurs affectés par des déformations lentes.
- l'évaluation de la vitesse et de l'accélération de la surface avec une précision millimétrique.
- l'identification de la source d'instabilité par analyse de mesures *in situ* et de données multi-temporelles de télédétection.

La surveillance régulière depuis l'espace des secteurs urbains offre une possibilité unique pour détecter les déformations précurseurs associées à une instabilité du sol, un élément essentiel pour la détection précoce et la réduction des risques dans des secteurs fortement peuplés. Les données satellites doivent être associées à une vérité terrain, parce qu'elles reflètent les mouvements des cibles, dont les déplacements réels ou apparents peuvent résulter d'une variété de causes de déformations (par exemple séismique, tectonique ou volcanique, mouvements de pente, de génie civil sous-terrain, exploitation et extraction de fluide/gaz, détérioration de structure, expansion/effondrement des sols).

Keywords: deformation, geological hazards, land subsidence, landslides, monitoring, remote sensing.

INTRODUCTION

Ground failures and ground instability hazards can be caused by natural geological and climatic processes (e.g. landslides and slope movements, soil volumetric changes in relation to dry and wet periods, soil/rock dissolution, oscillations of ground water levels, seismic and volcanic activity, neo-tectonic uplift or subsidence) or induced by anthropogenic sources (e.g. ground water pumping, gas and oil withdrawal, mining activity, subsurface and surface engineering works). Although the mechanisms and origins of these phenomena are quite variable and complex, they all produce the same surface effect, i.e. ground deformation. Furthermore, the failure or main instability phase is generally preceded by a period of slow deformation. It follows that the early detection and monitoring of surface displacements can represent, in particular in urban areas, a key effort of risk prevention or at least risk reduction.

Ground instability phenomena cover an extremely wide range of spatial and temporal scales, and are not uncommon in large, densely urbanised environments. However, even in the case of large cities, with high exposure to hazard, a regular *in situ* topographic monitoring of ground deformation is typically unfeasible due to the costs involved, or - at best - limited to the during or post-disaster period. Furthermore, towns and cities often represent a harsh setting for GPS or conventional topographic surveying and reliable measurements necessitate the use of skilled personnel.

It is now widely accepted that conventional methods used for detecting and monitoring natural hazards could benefit from the use of space-borne remote sensing systems because of the rapid and easily updatable acquisitions of data over wide areas, which reduce both field work and costs (e.g. CEOS DMSP Report 2002; IGOS GEOHAZARDS 2004; Wasowski, Lollino & Limoni *et al.*, 2004). Recent advances in optical and radar imagery capabilities (e.g. high spatial resolution, stereoscopic acquisition and high temporal frequency acquisitions), the development of new robust techniques based on the interferometric analysis of radar images, such as the Permanent Scatterers Technique (Ferretti, Prati & Roca 2001), and the possibility of integrating these data within a Geographical Information System (GIS) have greatly increased the potential of remote sensing for ground surface deformation monitoring and landslide investigations (e.g. Dehls, Basilico & Colesanti 2002; Wasowski, Refice & Bovenga et al. 2002; Colesanti, Ferretti & Novali *et al.* 2003*a*; Colesanti, Ferretti & Prati *et al.* 2003*b*; Colesanti & Wasowski 2004; Farina, Colombo & Fumagalli *et al.* 2004, Ferretti, Novali & Burgmann *et al.* 2004, Hilley, Burgmann & Ferretti *et al.* 2004). This paper addresses the use of advanced interferometric methods for detecting and measuring ground movements, especially in urbanised areas.

SAR INTERFEROMETRY AND THE PS TECHNIQUE

This section provides a short overview of the scientific background related to DInSAR and PSInSAR. More detailed information can be found in references (Gabriel, Goldstein & Zebker 1989, Massonnet & Feigl 1998; Rosen, Hensley & Joughin *et al*. 2000; Ferretti, Prati & Roca 2000; Ferretti *et al.* 2001; Colesanti *et al.* 2003*a*).

Satellite radar interferometry involves phase comparison of synthetic aperture radar (SAR) images, gathered at different times along the same nominal orbit. This technique has the potential to detect millimetric target displacements along the radar Line-Of-Sight (LOS) direction. A SAR image is a matrix of complex numbers. Amplitude values are related to local reflectivity (the amount of back-scattered energy), while phase values are sum of two contributions: local reflectivity and a quantity proportional to the sensor-target distance. The aim of the interferometric techniques is to highlight possible range variations of the target, by means of a simple phase difference between two images gathered at different times. If the local reflectivity remains unchanged in time (e.g. desert areas, Figure 1), its phase contribution disappears in the differentiation and possible range variations can then be detected. Since the wavelength of the illuminating radiation is usually only a few centimetres (SAR satellites available today operate at C-band, in the microwave domain), even a millimetric range variation translates in a phase change of several degrees that can be measured.

Apart from cycle ambiguity problems, limitations are due to temporal and geometrical decorrelation (i.e. the SNR – Signal to Noise Ratio), and to atmospheric artefacts. Temporal decorrelation makes interferometric measurements unfeasible where the electromagnetic signature and/or the positions of the scatterers change with time within the resolution cell, so that the reflectivity phase contribution cannot be supposed constant with time (e.g. vegetated areas). Reflectivity variations as a function of the incidence angle further limit the number of image pairs suitable for interferometric applications, unless the change is reduced due to a point-wise character of the target (e.g. a corner reflector). In areas affected by either kind of decorrelation, generating the interferogram no longer compensates the reflectivity phase contribution, and possible phase variations due to target motion cannot be highlighted. Finally, atmospheric heterogeneity creates an atmospheric phase screen superimposed on each SAR image that can seriously compromise accurate deformation monitoring (Figure 2). Indeed, even considering areas slightly affected by decorrelation, it may prove extremely difficult to discriminate the signal of interest and the atmospheric signature, at least using single interferograms.

In addressing this hurdle, the "Permanent Scatterer 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 subjects 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 referred to as Permanent Scatterers (PS). Their stability arises, almost always, as the result of a dominating scattering centre within the resolution cell.

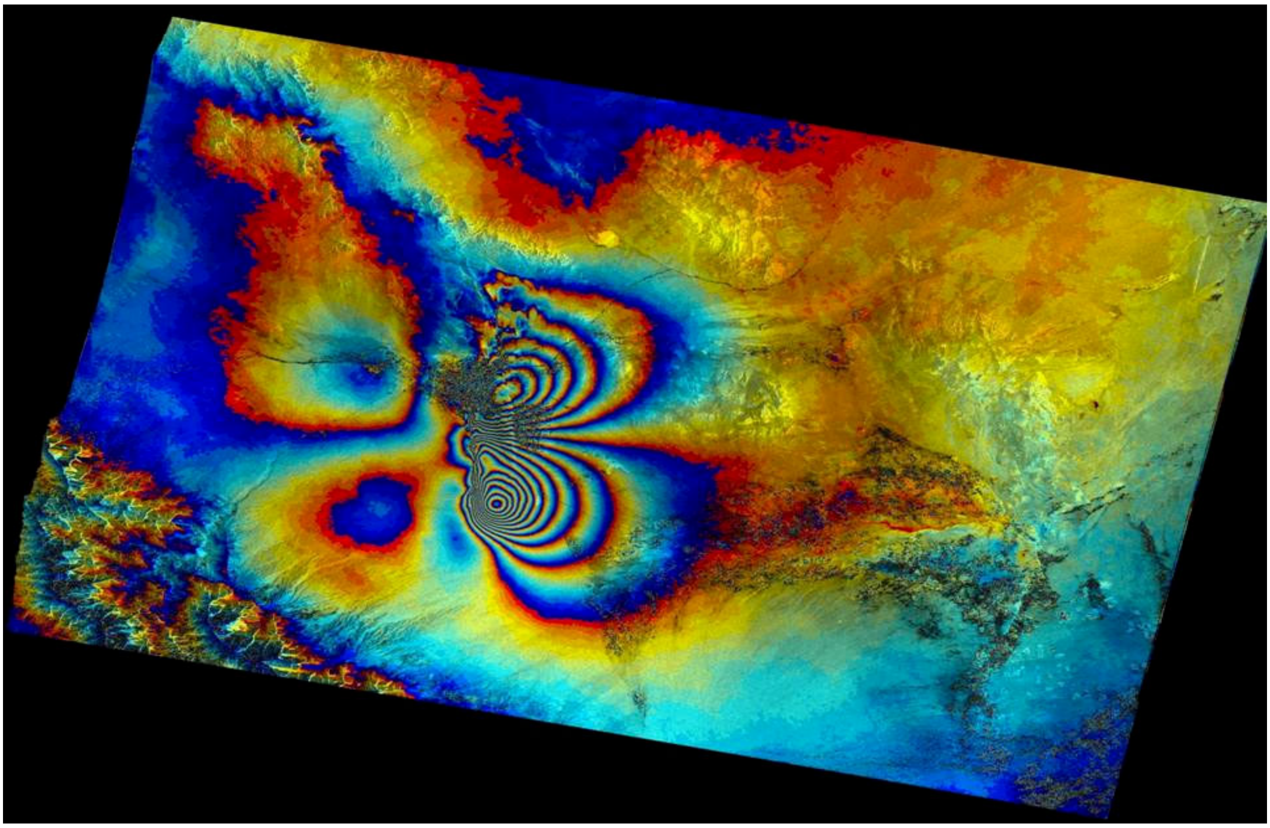

Figure 1. Example of differential interferogram – European Space Agency ESA-ENVISAT ASAR data. Phase data (colour coded) are superimposed on the amplitude image. The satellite radar sensor transmits microwave pulses and records both the amplitude and phase of the echoes reflected back from the Earth's surface. If one compares the phase of echo returns recorded from two passes acquired at different epochs, an estimate of the surface movement can be made. In this picture, the co-seismic deformation field of the Bam earthquake in Iran (December 26th, 2003; moment magnitude Mw=6.5) is reported. One fringe corresponds to 28 mm of LOS displacement. The city of Bam is in the area of maximum displacement.

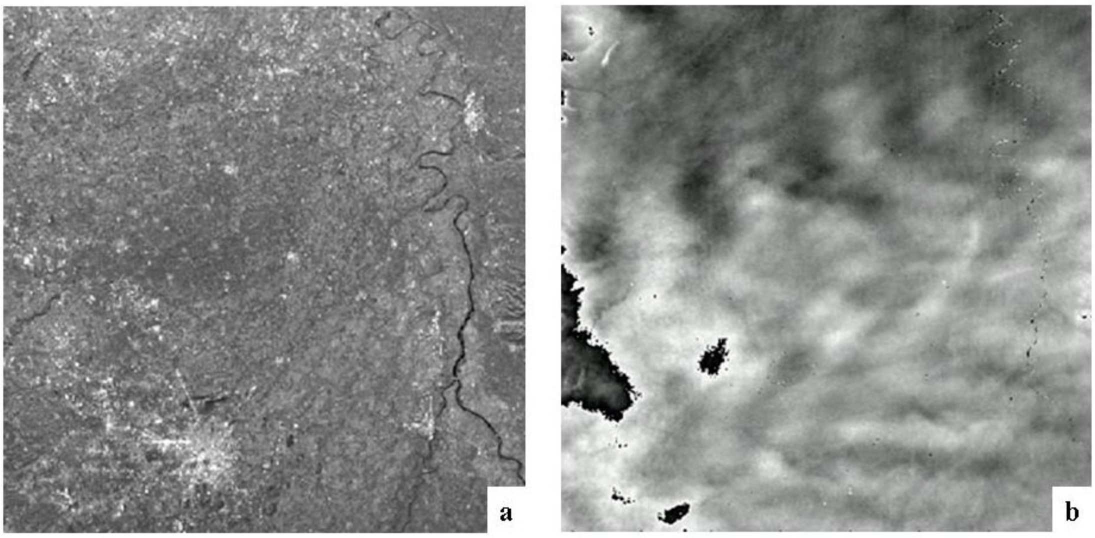

Figure 2. Example of SAR amplitude image (a) and interferogram (b) affected by atmospheric effects. Atmospheric heterogeneities usually do not impact on amplitude images but can seriously compromise interferometric measurements.

PS contain either natural objects, such as rock outcrops, man-made objects such as statues, lamp standards, antenna and other metallic structures on the roofs of buildings, or specially fabricated reflectors. More often than not, they are man-made objects. Figure 3 shows some typical examples of objects that reflect well.

Figure 3. Examples of Permanent Scatterers (PS), i.e. objects that exhibit a good stability of their radar return and allow interferometric measurements.

The PS approach is based on the following few observations. Atmospheric artefacts show a strong spatial correlation within every single SAR acquisition, but they are uncorrelated in time. Conversely, target motion is usually strongly correlated in time and can exhibit different degrees of spatial correlation depending on the phenomenon at hand (e.g. subsidence due to water pumping, fault displacements, localized sliding areas, collapsing buildings, etc.). Atmospheric effects can then be estimated and removed by combining data from a long time series of SAR images, such as those available in the ESA-ERS archive, based on data gathered since 1991. In order to exploit all the available images, and then improve the accuracy of the estimation, only scatterers slightly affected by both temporal and geometrical decorrelation are selected.

Possible stable and point-targets (i.e. the PS), are then detected on the grounds of the stability of their radar returns. This allows a pixel-by-pixel selection with no spatial averaging. Due to high spatial correlation of the atmospheric contribution, even a sparse grid of measurements may allow proper sampling of the atmospheric components, provided that the PS density is high enough. Of course, a sufficient number of images should be available (usually more than 20), in order to identify PS and separate the different phase contributions.

At the PS, sub-metre elevation precision and millimetric terrain motion detection (thanks to the high phase coherence of these scatterers) can be achieved, once atmospheric contributions are estimated and removed. In particular, relative target LOS velocity can be estimated very accurately (even better than 0.1 mm/yr in case of the long time span data). The higher the precision of the measurements the more reliable the differentiation between models of the deformation process under study. This is a key issue for risk assessment.

The final results of this multi-interferogram approach are the following:

- a map of the PS identified in the image and their coordinates: latitude, longitude (accuracy better than 5 m for most of the data-sets) and precise (better than 1 m) elevation;
- their average LOS velocity (precision better than 1 mm/yr in most of the cases);
- the estimated LOS motion component of each PS as a function of time.

Common to all differential interferometry applications, the results are computed with respect to a Ground Control Point (GCP) of known elevation and motion. All data can be easily imported in a GIS.

For example, Figure 4 shows the velocity field (in mm/yr) over the central part of Rome, estimated using 70 groups of SAR data acquired from 1992 to December 2000 by ERS sensors operated by the European Space Agency (ESA). The estimated *a posteriori* precision is 0.25 mm/yr. Satellite repeat-cycle is 35 days (about 10 acquisitions/yr). Areas affected by ground surface movements, i.e. local subsidence (negative sign of velocity), are clearly visible. This initial assessment is helpful to focus subsequent more detailed *in situ* investigations.

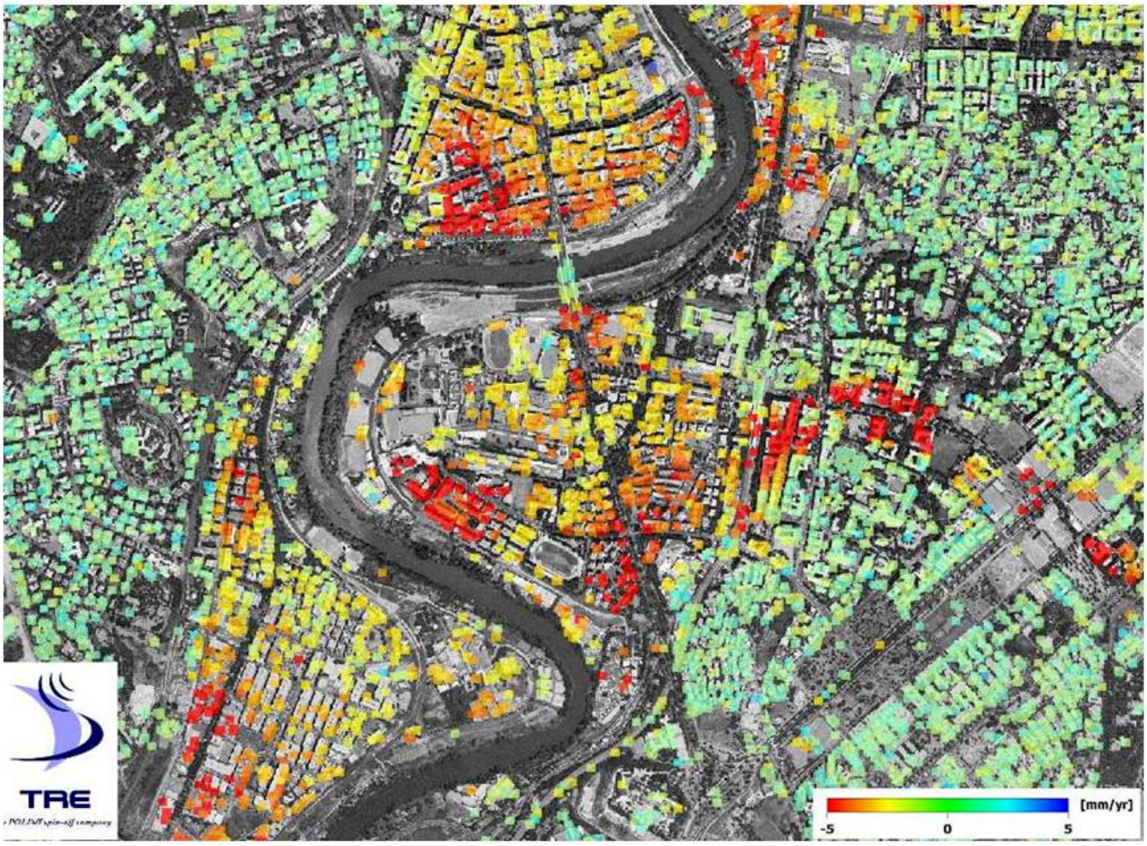

Figure 4. Example of PS results over Rome (Italy). Coloured dots correspond to Permanent Scatterers. The colour of each PS depends on the LOS velocity value in mm/yr (for visualisation purposes the velocities are saturated to +- 5 mm/yr). The background image is an aerial photo of the city. The analysis allows a fast identification of the areas affected by deformations, i.e. by local subsidence (SAR data: ERS-ESA© 1992-2000).

STRENGTHS AND LIMITATIONS OF THE PS TECHNIQUE

The PS Technique is a software-based (signal processing) technology. Its strengths and limitations and, indeed, those of any DInSAR analysis, derive from not just the capabilities of the algorithms implemented but also from the performance of the satellites and their SAR systems that provide the raw data input, as well as from the characteristics of the Area Of Interest (AOI). The strengths and limitations attributable to the satellites and their SAR systems available today (2005) are summarized in Table 1.

Table 1. Strengths and Limitations of SAR systems

Strengths	Limitations
• Two satellites are available today for InSAR analyses: ESA's ENVISAT and Canadian RADARSAT. • Retroactive analysis, back to 1992, is possible using the ESA-ERS satellites' data archive. • Analyses over thousands of square kilometres are possible and require a limited amount of time. • Resolution cells (pixels) are becoming smaller, enhancing the spatial accuracy of PS location and the PS density. • At least 3 new satellite sensors will be available in the next 2 years. A weekly update of the information will become feasible. • Each AOI is illuminated by at least two orbits: one ascending (from South to North) and one descending (viceversa). Data acquired from two independent acquisition geometries can allow internal cross-checks and a better evaluation of the local displacement field.	• C-band signals (wavelength: 5.66 cm) cannot penetrate vegetation and back scatter to the satellite. • Steep terrain can prevent the radar signals reaching areas in the 'shadow' of the line of sight. • Nowadays sensors are not specifically designed for InSAR applications. • Satellite repeat-cycle is 35 days for ESA sensors and 24 days for RADARSAT. • If prior information on ground motion is unavailable, phase unwrapping problems (phase aliasing) limit the maximum displacement between two consecutive acquisitions to less than 14 mm (for C-band sensors available today). • Although the combination of data acquired along both ascending and descending orbits can help in distinguishing vertical and horizontal deformation, a full 3D displacement field cannot be recovered.

From the perspective of the technology itself, the principal strengths and limitations of the PS Technique are summarized in Table 2.

Table 2. Strengths and Limitations of the PS Technique

Strengths	Limitations
• For some areas target velocity can be estimated with unprecedented precision (up to +/- 0.1 mm/yr) by exploiting all the images acquired over the area of interest. • Measurement, in millimeters, of the 'vertical' dimension being more precise than that of GPS. • Provides a spatial density of measurement points not achievable with conventional techniques (PS density can be >300 PS/sqkm in urban areas). • The ability to recover the displacement time series of each PS with high precision. • Geocoding accuracy is usually better than 4-5 m. • Artificial reflectors can be deployed in areas where no "natural PS" are available and the PS technique can be successfully applied using artificial reflectors.	• Difficult to infer the PS distribution in an area without processing a significant number of SAR images. • Interferograms can only be generated from SAR data acquired by the same satellite. • >20 SAR images needed to identify PS. For some areas not enough data is available to run the processing. • Satellite repect-cycle (35 days for ESA sensors and 24 days for RADARSAT satellite) is still too long for some applications. • Not all the man-made structures act as PS. If the user is interested in gathering information on a particular site (e.g. a bridge or a dam), there is a possibility that no PS is present there.

APPLICATIONS

The impact of the PS technique on the potential users depends very much on the application at hand. In general, the probability of success in performing a PS analysis depends on: (1) the number of data available and their temporal distribution; (2) the PS density in the AOI; (3) the motion of the targets with respect to the satellite line-of-sight; (4) the presence of snow coverage. In the following, a brief summary of different PS applications is reported. For more details the readers are referred to the cited literature.

- **Subsidence analysis -** Both temporal and spatial resolution of the SAR satellite data are well suited for monitoring urban subsidence and terrain settlement such. PS density in urban areas is usually greater than 100 PS/sqkm and thousands of square kilometres can be monitored monthly (Ferretti *et al.* 2000). The recent results obtained in the framework of the ESA Terrafirma project (www.terrafirma.eu.com) have confirmed the theoretical analysis. Suburbs and even individual buildings affected by subsidence can be detected (Ferretti *et al.* 2000), as well as possible seasonal movements induced by the water table variations (Colesanti *et al.* 2003*a*). Many examples of PSInSAR technique applied to subsidence studies are available at TRE web-site (www.treuropa.com). Companies of the oil and gas sector are currently the major users of PS data. Precise surface deformation fields can be very valuable for reservoir exploitation (Vasco & Ferretti, 2005) and for identification of areas, in the neighbourhood of the oil or gas wells, which can suffer damages. Subsidence induced by mining activities can be also detected by means of PSInSAR (Colesanti, Le Moulic & Bennani *et al.* 2005). In Figure 5 the PS velocity field of Tokyo (Japan) is reported. Considering the high rate of seismic and tectonic activity of the region, it is likely that the local deformations (e.g. linked to spatially limited subsidence in the Tokyo harbour area) are superimposed on terrain motion related to larger scale geological phenomena.
- **Seismic fault and volcano monitoring -** For seismic fault monitoring a very high precision is usually required, because terrain motion can be extremely slow (e.g. Massonnet & Feigl 1998). Moreover, higher precision means more acurate models of fault dynamics and better evaluation of seismic hazard. PS data can play a major role for two reasons: (1) density of PS measurements is orders of magnitude greater than what is feasible by using permanent GPS stations; (2) vertical precision of PSInSAR is higher than that of GPS. Indeed, PS and GPS data are somewhat complementary: GPS is capable to provide a continuous 3D monitoring of a limited number of benchmarks, whereas, at present, PSInSAR allows a monthly update of possible range variations of thousands of radar targets. Although synergistic strategies for an integrated use of both systems are still under study, it is now widely accepted that PS and GPS are not competitor technologies, and should be jointly exploited for the monitoring of areas at risk. Clearly, wide-area coverage of PS data leads to a better identification of the possible locations for permanent GPS stations, highlighting sites affected by deformations induced by anthropogenic sources rather than by tectonic or volcanic motions (e.g. Salvi, Atzore & Tolomei *et al.* 2004). A recent example of PSInSAR application in a region characterised by the presence of several seismically active faults and high rate of tectonic deformations (the San Francisco Bay area) is reported in Ferretti *et al.* 2004 and Hilley *et al.* 2004. An example of the joint use of DInSAR and classical geodetic techniques for monitoring volcanic caldera unrest episodes near the city of Naples (Italy) is given in Lanari, Berardino & Borgstrom *et al.* 2004.

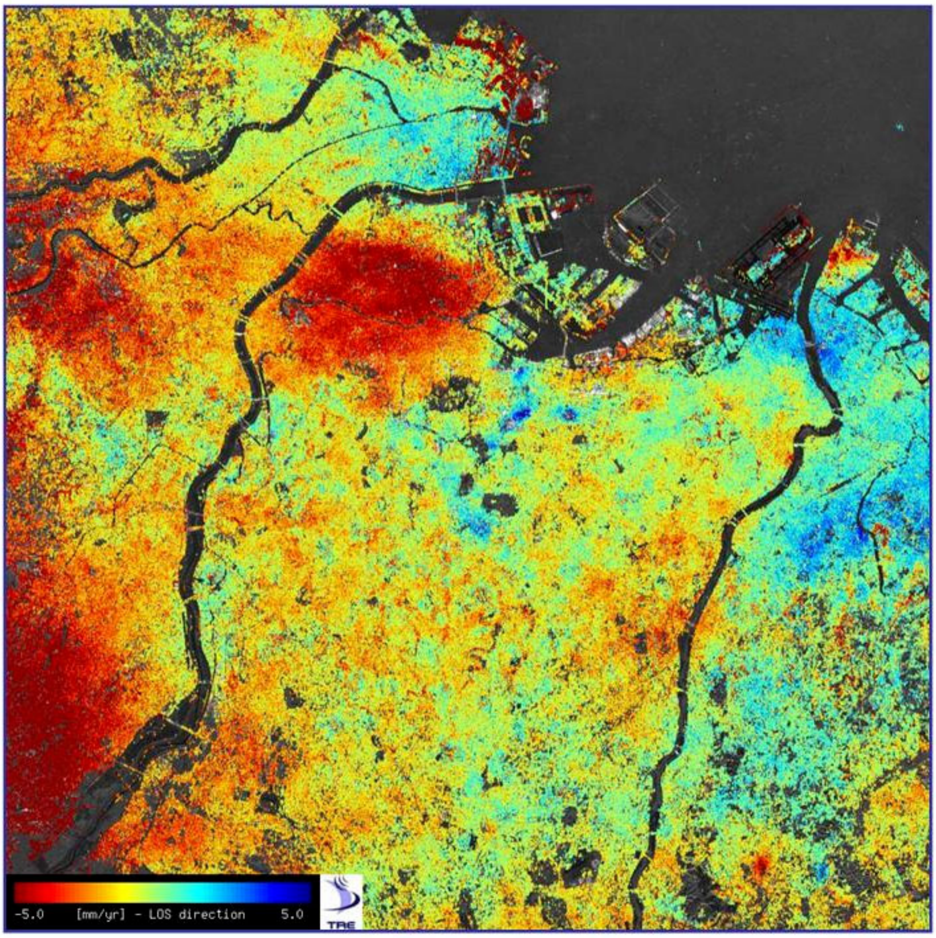

Figure 5. The intriguing velocity field estimated from 40 radar scenes acquired over Tokyo, Japan (SAR data: ERS-ESA© 1992-2000); for visualisation purposes the velocities are saturated to +- 5 mm/yr. The subsidence affecting the harbour area is clearly visible.

- **Slow landslide detection and monitoring -** PSInSAR measurements, combined with information regarding mechanism of movement and failure geometry derived from conventional in-situ data, constitute a useful tool for wide-area slope instability detection and site-specific monitoring of slow landslides (Colesanti *et al.* 2003; Colesanti & Wasowski 2004; Farina *et al.* 2004; Hilley *et al.* 2004; Ferretti *et al.* 2005). Although the limitations of the PSInSAR application to landslide analysis are still severe (Table 1 and Table 2), the possibility to create very quickly precise velocity fields over wide areas by exploiting historical archives of SAR data opens new scenarios for a regional scale mapping of the slope deformation phenomena and can assist in the generation of landslide inventory maps (e.g. Farina *et al.* 2004;). PSInSAR can lead to the wide-area distinction between unstable and stable slopes. The rate of movement can also be estimated where displacement velocities are lower than 5-6 cm/year. The possibility of a regular update of surface deformation data-sets over large areas and the possibility of easy integration of PS data and in situ information within a GIS have greatly increased the potential of SAR remote sensing for landslide investigations. It is expected that with a growing number of documented case histories and with more depth analyses it will be possible to achieve in the near future a better evaluation of the real impact of this technology on landslide inventory projects. The gallery of applications of PSInSAR to unstable hillslope areas (see Figure 6 and other examples at www.treuropa.com) is continuously increasing, in particular in Italy, where landslide hazard is widespread and the technology is gaining consensus. Indeed, Public Administrations at national and regional level are now asking for PSInSAR monitoring data.
- **Monitoring individual structures -** Motion measurements with millimetric precision are required for the application of PSInSAR to structure stability assessment. Moreover, more than one PS should be available on the target, asking for sensors characterized by high spatial (and temporal) resolution. Today this kind of analysis is possible only over rather large structures (e.g. dams, viaducts, large public buildings). The possibility to deploy (passive) artificial reflectors to create a geodetic network for single building monitoring is a promising research area that can enlarge significantly the field of application of PSInSAR. However, different *in situ* effects should be well studied and modelled. Certainly, a historical archive of radar data can contribute to verifying the cause-effect connection between, for example, the construction of a new tunnel and damage occurring to facilities in the neighborhood of the excavation area. Indeed, PS data have already been used as evidence in lawsuits (e.g. Jurina, 2003).

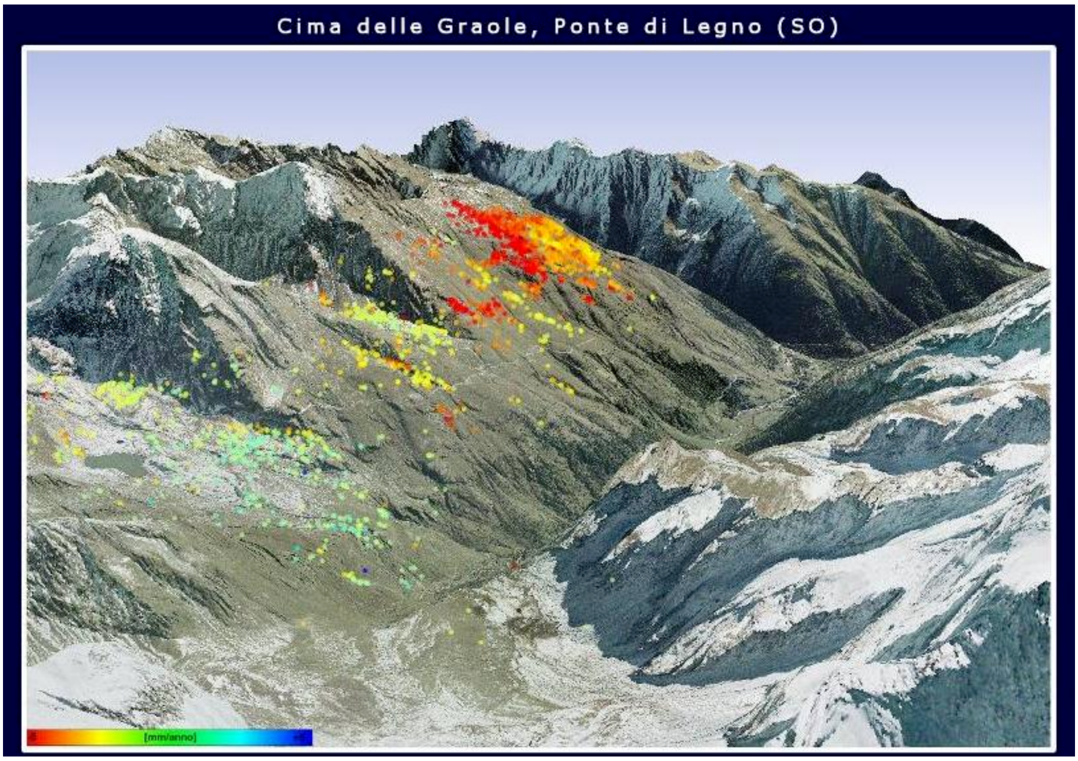

Figure 6. This provides an example of PS analysis used for the identification of an area affected by a slow slope deformation phenomenon in Lombardy (Italy – Alpine area). PS analysis lead to the estimation of the displacement rates and to the preliminary re-assessment of the areas susceptible to landslide hazard (SAR data: ERS-ESA© 1995-2000); for visualisation purposes the velocities are saturated to +- 5 mm/yr.

DISCUSSION AND CONCLUSIONS

The significant progress made in SAR interferometry in recent years has been accomplished despite the fact that the radar sensors on which the technology depends were designed for other purposes. This achievement has now prompted space agencies to mandate interferometric data capture as a pre-requisite of future SAR missions.

To this end, special attention is now being paid to the following issues:

- Acquisition policy: to create historical archives at least on a regional level. The ESA ERS archive is a clear example of the potential related to continuous satellite data acquisition. A successful DInSAR application requires regular acquisition of SAR data.
- Good attitude and high orbit stability of the satellite platform: to reduce geometrical decorrelation and to improve the quality of the interferogram.
- High accuracy of satellite state vectors: to limit systematic errors.
- Low repeat cycle: to minimize temporal decorrelation effects.

Looking at the future, although the satellite mission SENTINEL, the new ESA SAR mission to be launched before 2009, within the framework of the GMES program, will be specifically designed for InSAR applications, the data sources available today will be supported before the end of 2006 by three new missions operating at three different frequencies: RADARSAT-2 (C band, 5.4 GHz), ALOS-PALSAR (L-band, 1.27 GHz) and TerraSAR-X (X-band, 9.6 Ghz). Moreover, the Italian dual-use constellation of remote sensing satellites (Cosmo-SkyMed) should start the acquisition of SAR data in X band, in 2007.

The impressive spatial resolution of TerraSAR-X and RADARSAT-2, as well as the potential of the L-band sensor mounted on ALOS, which will be capable of monitoring faster phenomena and be less prone to phase decorrelation, should open a completely new scenario in ground deformation detection, monitoring and forecasting. These new sensors, in synergy with GPS, laser scanners and other *in situ* instruments, will enlarge exponentially our possibilities to effectively monitor unstable areas. The joint use of more than one mission will increase significantly the temporal sampling of a geo-hazard under study and weekly updates of information are expected to be realized by 2007. Also, the higher spatial resolution of future SAR sensors will lead to smaller artificial reflectors than those in use today. The latter can be applied whenever "natural" radar targets are unavailable in an AOI, e.g. in heavily vegetated and forested areas. These small passive reflectors will probably represent a breakthrough also for pipeline monitoring and, in general, for the analysis of key structures in vegetated areas.

As illustrated by Wasowski *et al*. (2004), the integrated use of periodic satellite radar observations for monitoring ground deformations in urban areas is needed for local authorities, planners and developers, to advise on: (i) which of the areas affected by ground instabilities are most prone to future failures and (ii) what engineering actions are needed to mitigate or reduce the actual or potential geohazard and to keep the risk of failure low. In particular, in seismically, volcanically and tectonically active environments it will be useful to develop an integrated strategy of localised in situ monitoring, assisted by wider area, systematic satellite radar observations. This data can provide a spatial overview, both of historic and contemporary ground surface deformations affecting a given area. The data can be geo-referenced, usefully stored at suitable scales and accessed through GIS. In addition, the integrated approach to the problem may also help to detect the development of anomalous strains where ground stability may be decreasing. This in turn may lead to the detection of precursory deformations associated with the initiation of ground instability, a key element for early warning and hazard mitigation in highly populated areas.

At present, however, the interpretation of the exact significance, in terms of cause-effect, of the millimetric-centimetric ground surface displacements detectable by PSInSAR remains difficult, even when some ground truthing is available. Futher research focused on the applications of well integrated *in situ* and SAR interferometry investigations in different tectonic environments and hydro-geotechnical settings is still needed. Nevertheless, it is apparent that over wide areas the surface displacements, where truly reflecting ground strains and not structure deterioration, are likely to be mainly of volumetric nature (e.g. swelling/shrinking of soils). Clearly, in the large urban environments the anthropogenic influences are expected to be significant, but other factors such as neotectonics may also represent an important force driving ground deformations, especially in seismically and volcanically active regions. Regardless the exact cause-effect linkage, even the most simple, qualitative distinction between the stable and deforming ground constitutes a valuable input for a preliminary assessment of potential ground instability hazard. Furthermore, the periodic satellite-based remote sensing offers an attractive possibility of a regular survelliance of wide-areas and timely detection of localised ground deformations. Following the initial assessment it will thus be possible to focus attention on the areas where a potential hazard may be developing and where more detailed PSInSAR analysis and geotechnical investigations may ultimately be required.

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