Permanent Scatterers technology: a powerful tool for historic and future monitoring of landslides and building settlements

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ABSTRACT: This paper discusses the use of multiple image sets of SAR data acquired by past and current satellite platforms in monitoring landslides and other terrain instability issues. The basic mathematical model is presented, highlighting the critical parameters of interferometry in geological and geotechnical applications. The potential of the technology and its drawbacks related to availability of long temporal series of SAR acquisitions are also discussed. Extensive processing of many SAR scenes has demonstrated how multi-temporal data-sets can be successfully exploited for terrain monitoring, by identifying objects on the landscape that have a stable, point-like behaviour. These objects, referred to as Permanent Scatterers (PS), can be geo-coded and monitored for movement very accurately, acting as a "natural" geodetic network. The paper presents examples of applications of monitoring landslides, settlement and subsidence, using experience in Italy and Canada, and concludes with a discussion on future directions for InSAR.

1. INTRODUCTION

Landslides represent one of the most diffuse natural hazards in many parts of the world, threatening and influencing the socio-economic conditions of many countries (Schuster, 1996). Due to the difficulties of putting countermeasures into effect in terms of mitigation works, a deep knowledge of landslide distribution and state of activity is required, especially for those situations where property and infrastructure are exposed.

Conventional methods used for detecting and monitoring slope instability could benefit from the use of remote sensing systems due to the rapid and easily updatable acquisitions of data over wide areas, which reduce both field work and costs (Soeters and Van Westen, 1996).

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 et al., 2001), and the possibility of integrating these data within a Geographical Information System (GIS) have dramatically increased the potential of remote sensing for landslide investigations (Farina et al, in review). This paper addresses the use of interferometric methods for measuring ground movement.

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing tool capable of measuring small displacements of the earth's surface, across large areas. The first generation of InSAR technology emerged in the mid-90's and was referred to as Differential InSAR, or DInSAR. It measured the displacement within an area of interest (AOI), along the line of sight of the radar beam, between two points in time represented by two SAR images, or scenes. With SAR systems operating in the microwave domain, phase shifts between pairs of images enabled displacements to be measured to millimeter accuracy. As experience in the use of DInSAR progressed, it became evident that accuracy was often severely affected by the atmospheric contribution to phase shift and, at that time, the ability to remove it did not exist. This led researchers to devise methods for identifying the atmospheric contribution and, in 1999, the

Politecnico di Milano pioneered a multi-interferogram approach that identified, quantified and removed atmospheric distortions, leaving displacement as the only remaining contribution to signal phase shift. Described as the Permanent Scatterers Technique (PS Technique), it has been used in tectonics and for assessing geotechnical hazards such as landslides, settlement and subsidence.

In the context of these applications of InSAR, by observing the response to triggering factors and the effectiveness of mitigation measures, the measurement of surface displacement of land, induced by mass movement, often represents the most effective means for defining the behavior of a geo-hazard. InSAR measurements, combined with information regarding mechanism of movement and failure geometry derived from conventional in-situ data, constitutes a useful tool for understanding the geo-hazard's dynamics and its probable future evolution.

2 THE PS TECHNIQUE

The PS technique takes DInSAR technology to a higher plane. At the heart of both technologies is the differential interferogram: a complex image displaying the change in signal phase between a pair of SAR scenes. The basic model that defines signal phase is:

$$\varphi = \psi + \frac{2\pi}{\lambda} . 2r + \alpha + noise \qquad (1)$$

where φ = phase; ψ = reflectivity of an object or pixel; r = the distance between the satellite and the target; α = the atmospheric contribution, and λ = signal wavelength.

It follows that, when looking at change between a pair of scenes, the phase shift $\Delta\varphi$ can be expressed as:

$$\Delta\varphi = \Delta\psi + \frac{4\pi}{\lambda} . \Delta r + \Delta\alpha + noise \qquad (2)$$

For both images, if ψ remains the same and if we have identical atmospheric contribution as well as low noise energy, then the expression for phase shift becomes:

$$\Delta\varphi = \frac{4\pi}{\lambda} . \Delta r \qquad (3)$$

where Δr is the range variation possibly due to target motion.

If nothing is known about the direction of motion, the phase shift could be reflecting 'upward' or 'downward' motion. In order to remove this ambiguity, the upper limit of phase can only be one-half of the signal phase. In other words, the maximum displacement between any pair of radar scenes would be one-quarter of the signal's wavelength. However, when the direction of movement is known, the ambiguity is removed and the maximum measurable displacement between a pair of scenes becomes one-half of the wavelength.

All European and Canadian satellites carry/carried C-band SAR whose wavelength is 56mm. Therefore, the two upper limits of movement discussed in the previous paragraph would be 14mm and 28mm, respectively.

While a tolerance for marginal differences in reflectivity and noise between images can be accommodated, the remaining contributor to phase – atmospheric distortion – cannot be tolerated and has to be removed. With only two images to analyze in DInSAR, identifying the presence of atmospheric artifacts, quantifying them and then removing them is an impossible task.

In addressing this hurdle, the PS Technique takes advantage of long temporal series of SAR data of an area, acquired by the satellite on the same orbit, to filter out these atmospheric artifacts. It does so by generating multiple differential interferograms from a set of radar scenes, and subjects them to numerical

and statistical analyses from which a sub-set of image pixels are identified 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 an object within the resolution cell. The threshold of image acquisition on which a PSInSAR model can be developed, for any application, lies between 15 and 20 SAR scenes.

PS contain either natural objects, such as rock outcrops, man-made objects such as statues, lamp standards, heating and ventilating structures on the roofs of buildings, or specially fabricated reflectors. More often than not, they are man-made objects. Figure 1 shows some typical examples of objects that reflect well.

Figure 1. Typical objects that can produce a strong reflectivity

There are two processing stages. Firstly, the atmospheric effects are estimated and removed from every interferogram and, then, a pixel-by-pixel

analysis searches for all PS within the AOI, jointly estimating and removing elevation effects in the interferogram, and generating the time series of their line-of-sight displacements.

Because the PS data are in a digital form, they can be conveniently downloaded on to a GIS platform. When layered over an high resolution ortho photo on the same GIS platform, the position of the PS can be observed. The PS Technique shows these PS as a colored dot, see Figure 2, whose color represents the average displacement rate across the whole time frame. Each PS is geo-referenced and a data base stores the displacement behaviour.

The displacement vs. time series for each PS, an example of which appears in Figure 3 shows the motion of an individual PS relative to a reference point within the data set that has displayed stable properties and, can be assumed to be static.
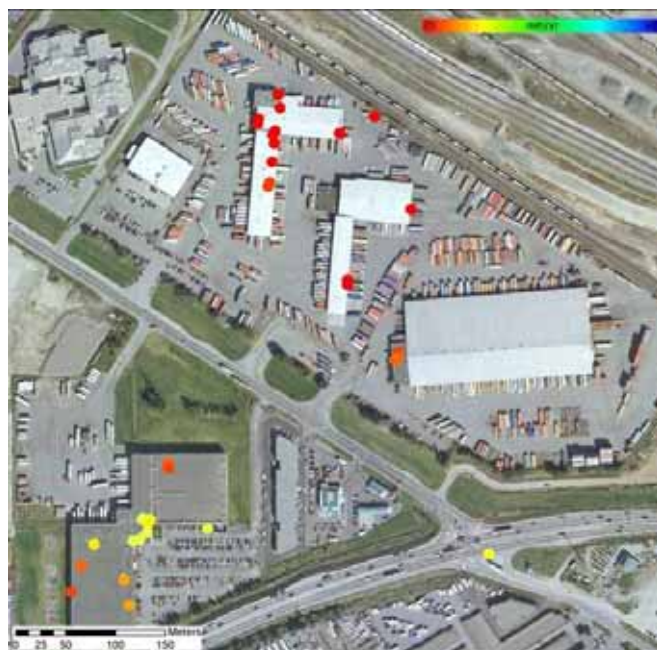

Figure 2. Typical image from a GIS platform showing the location of PS overlying High resolution ortho photos.

PS data copyright Tele-Rilevamento Europa srl
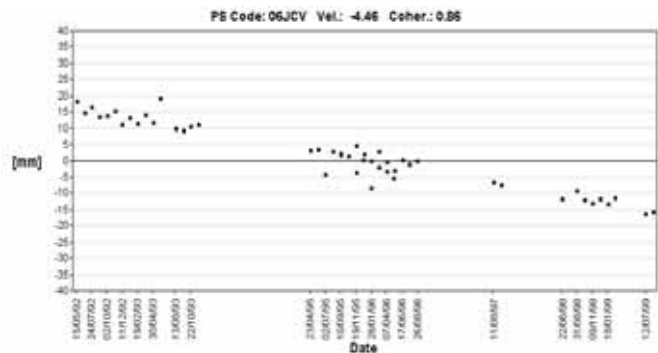Orthophotos by McElhanney Consulting Services and courtesy of BC Ministry of Transportation

Figure 3. A typical PS time vs. displacement series.

3 STRENGTHS & LIMITATIONS OF THE PS TECHNIQUE

3.1 *General*

The PS Technique is a software-based technology. Its strengths and limitations and, indeed, those of any DInSAR analysis, derive from not just the capabilities of the software but also from the performance of the satellites and their SAR systems, which provide the raw data input and the characteristics of the AOI.

3.2 *Strengths & Limitations of SAR systems*

The strengths and limitations attributable to the satellites and their SAR systems are summarized in Table 1.

Strengths
• Retroactive analysis, back to 1992, is possible because of the ERS satellites' data archive;
• Newer, more sophisticated satellites offer flexibility in image acquisition modes and polarizations;
• Resolution cells (pixels) are getting smaller, enhancing the spatial accuracy of PS location and the PS density.

Limitations
• C-band signals cannot penetrate heavy vegetation and back scatter to the satellite;
• Steep terrain can prevent the radar signals reaching areas in the 'shadow' of the line of sight.

Table 1. Strengths & Limitations of SAR systems

3.3 *Strengths & Weaknesses of the PS Technique*

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

Strengths
• generation of a displacement trend, and changes thereto, over time;
• measurement, in millimeters, of the 'vertical' dimension being more accurate than that of GPS;
• provides a spatial density of measurement points not achievable with conventional techniques;
• the ability to monitor movement within discrete temporal sub-sets of a full data set.

Weaknesses
• difficult to infer the PS distribution in an area without significant data processing;
• interferograms can only be generated from SAR data acquired by the same satellite;
• if prior information on ground motion is unavailable, phase unwrapping problems (phase aliasing) limit the maximum displacement between two consecutive acquisitions to less than 14mm.

Table 2. Strengths & Limitations of the PS Technique

4 APPLICATION OF THE PS TECHNIQUE TO LANDSLIDES

This section of the paper discusses the results of applying the PS Technique to the monitoring of the Castagnola landslide, a mass movement affecting a small village located in the Italian Apennines. The PSInSAR analysis, using a data set of SAR images acquired by both the ERS-1 and ERS-2 satellites,

provided ground displacement measurements of the unstable area within the time interval of 1992-2001. The InSAR measurements were integrated with in-situ measurements and traditional geomorphological investigations.

The area of interest (AOI), comprising at least 40 ha, is situated in the northern Apennines, a few tens of km to the east of Genoa, close to the Cinque Terre.

The landslide is located on a southwest facing slope with an average inclination of 12°, on the right bank of the Castagnola River. It is approximately 1400 m long with average and maximum widths of 400 m and 600 m, respectively. The limits of the unstable area comprise the Rio Rovereto – a right-bank tributary of the Castagnola River – to the southeast, and by several parallel NE-SW oriented faults on the northwest border. Along the landslide several morphological features are recognizable, indicative of recent movements. They are: the main scarp located in the upper portion of the slope at an elevation of 380 m; a lower scarp at an elevation of 300 m comprising the NW flank of the landslide; at least three evident slope ruptures, characterized by counter slope gradients, which have created a terraced morphology and, generally, a hummocky topography in the lower slopes.

The landslide activity has disrupted vegetation coverage which, in the slide area, now consists of sparse olive trees, rows of vines and bushes, delineating a noticeably different pattern with respect to the surrounding stable area. The instability conditions of the area have been recognized for a long time, attested to by the abandonment of several human settlements during the last three centuries.

The landslide can be classified as having a deep-seated gravitational movement of clayey terrains belonging to the Argille a Palombini Formation as the stratigraphic outcrop, overlying bedrock consisting of ophiolitic rocks (serpentinites and peridotites). By looking at the failure geometry the landslide corresponds to a complex movement with translational and rotational components. Several shallow movements composed of debris deposits overlie the main landslide body. The Castagnola landslide is currently active, confirmed by inclinometer readings acquired since 2001, which recorded deformation rates of up to several cm/year in the most active sectors of the slide, occurring on multiple rupture surfaces.

Rainfall and the weakness of the natural materials together with their intense jointing, have been identified as the main triggering factors. The landslide represents a serious socio-economic threat to the village of Castagnola, causing damage to several buildings and the migration of a large portion of the community away from the village.

The results of the PS analysis shown that rural areas seldom display a PS density comparable to that of urban areas. However, the AOI has produced a good distribution of coherent scatterers in the unstable area and among sparse vegetation. In addition, the slope exposure to the satellite line of sight has minimized the geometrical effects induced by the side-looking geometry of SAR systems. The spatial distribution of movements retrieved by the radar measurements matches the boundaries of the landslides, as mapped from geomorphological surveys by geologists of the Provincia di La Spezia, the public authority in charge of landslide mitigation. Of particular note, the radar data have confirmed the stability of the northern border of the landslide, the area chosen for construction of new settlements following abandonment of the most active zones. In the central portion of the slide, where the village is located, displacement rates have been measured ranging from 30 to 40 mm/year. The landslide activity identified by the PS corresponds very well with the distribution of damaged buildings and roads. A qualitative comparison between the radar measurements and the inclinometer readings, even though the two datasets were acquired during

different periods (1992-2001 vs. 2001-2002), has shown a good agreement, in terms of direction of the ground deformations and deformation rates. In fact, taking account of the acquisition geometry of the satellite for descending orbits, the radar measurements are compatible with the SW downslope direction of movement recorded by the inclinometers. The analysis of the temporal evolution of the landslide activity during the time interval 1992-2001 included an examination of the time series of displacement at each PS analysis, samples of which are shown in Figures 4 and 5
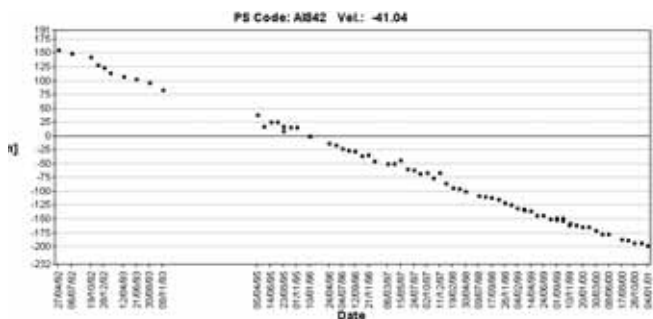

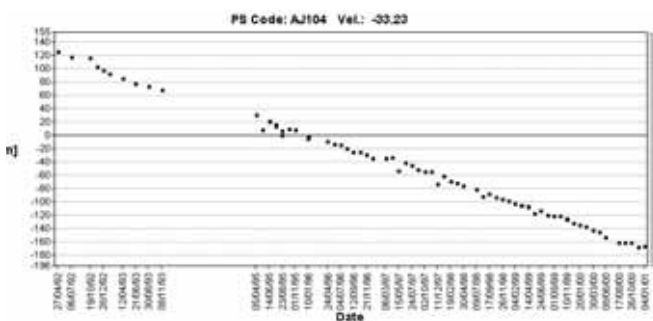Figure 4. Time vs Motion series for PS AI842

Figure 5. Time vs Motion series for PS AJ104

Although the data correspond to different types of displacement measurements (line-of-sight surface displacement from SAR vs. deep displacement from the inclinometer readings) and the period over which measurements were made spanning different time periods (the last radar image having been acquired in January 2001, while the inclinometer data span the time interval May 2001-March 2002), a qualitative comparison was carried out. The cumulative

displacement measured at the S10 inclinometer between May 2001 and March 2002 shows that while the slope of the first part of the curve is in agreement with the velocity measured by the PS AI842 of about 40 mm/year, movement seems to have accelerated since September 2001, as demonstrated by the increased steepness of the curve. The same behaviour has been recorded at the S5 inclinometer with the acceleration occurring after June 2001. The two PS close to these instruments are measured an average yearly displacement of 25-30 mm/year, lower than the corresponding rates of the PS located in the upper portion of the landslide. This variation in settlement rates between the landslide toe and the detachment zone was also confirmed by the inclinometer readings which, for example, recorded maximum displacements of 90 mm at S10 and 45 mm at S5.

Similar results were obtained in Rovigo (2002) and in Laino Castello (2005), in the Northern and Southern part of Italy respectively.

5. APPLICATION TO OTHER GEO-HAZARDS IN THE VANCOUVER AREA

The PS Technique has application beyond landslide detection and monitoring. Subsidence and settlement are well known hazards in development of infrastructure and commercial and residential property. This section of the paper discusses its application to a wide area in which a number of geophysical phenomena occur.

SAR data have been processed using the PS Technique in an area of approximately 8,000 Km² of the greater Vancouver area, from Horseshoe bay in the West, to Abbotsford in the East, and from the North Shore mountains in the North, to the City of Bellingham (USA), in the South. This area includes very deep Fraser River delta deposits as well as valley uplands formed by thick glacial deposits and bedrock-controlled mountain slopes. Part of this area is shown in Figures 6a and 6b and illustrates the

settlement and uplift characteristics at the land surface, above the various geological structures.
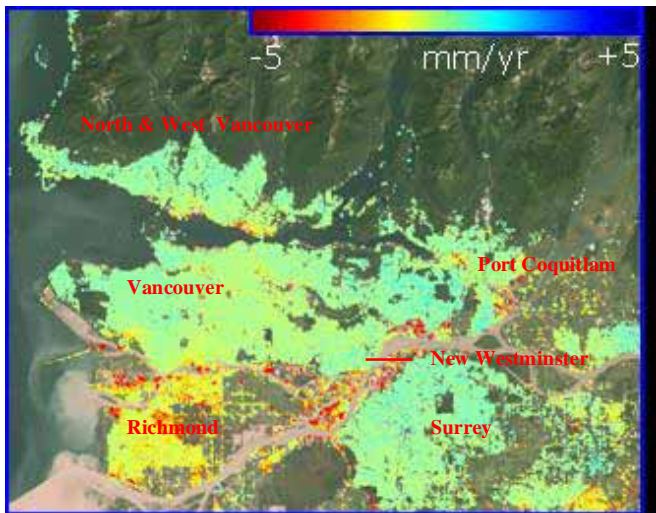

Figure 6a. Results of the PSInSAR analysis of the western extension of the greater Vancouver area.
PS data copyright of Tele-Rilevamento Europa srl.

The coloration represents displacement rates, in the line of sight of the radar beam, obtained from a PSInSAR analysis of SAR images acquired by the ERS-1 and ERS-2 satellites, spanning the period from 1992 to 2003.
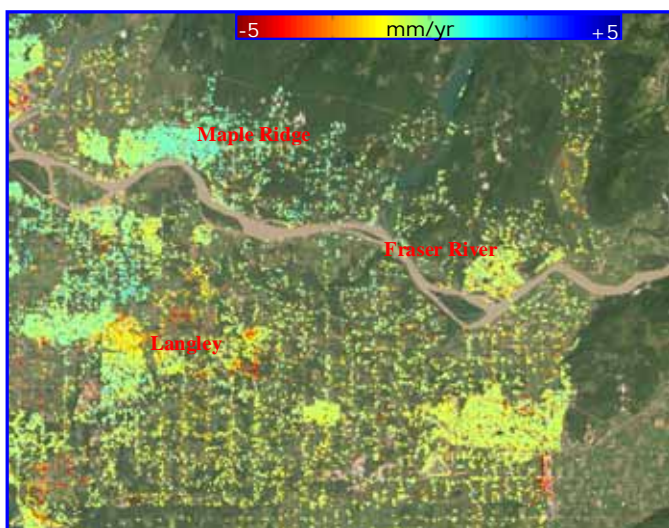

Figure 6b. Results of the PSInSAR analysis of the eastern extension of the greater Vancouver area.

The alluvial and deltaic areas are settling with the Cities of Richmond and New Westminster being most affected. Figure 7 shows the settlement trends in the waterfront area of New Westminster. The uplands are spread throughout the area, characterized by large tracts of the Cities of Vancouver, Surrey, Maple Ridge and Port Coquitlam. Generally, these lands are either stable or are uplifting at a maximum displacement rate of 1mm/year, suggesting the possibility of tectonic effects. Similarly, the Cities of West and North Vancouver, the District of North Vancouver and the Cities of Port Coquitlam and Maple Ridge are partly built on the lower slopes of the Coast Mountains where, again, slight uplifting can be observed in the order of 0.5 to 1mm/year at the higher elevations.
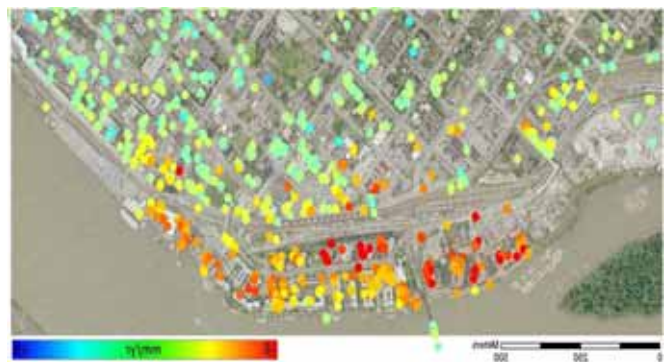

Figure 7. The results of a PSInSAR analysis of the waterfront area of the City of New Westminster. The area to the north is typical upland showing the stable to slightly uplifting behaviour.

PS data are copyright of Tele-Rilevamento Europa srl
Orthophotos by McElhanney Consulting Services

The contrast in PS density between urban and rural areas is well illustrated, particularly in Figure 6b, an area of greater agricultural activity than that shown in Figure 6a.

An anomaly to the general pattern of upland displacement behaviour can be seen in the City of Langley, an area of higher elevation, where the City overlies deep soft clays with significant peat content. Large tracts of the City settled between 2 and

4mm/year, throughout the time period of the analysis.

Given that the processed SAR data can be downloaded on to a GIS platform, it is possible to drill down to observe small, local sub-areas and, subject to the resolution of the underlying ortho photos, it is often possible to detect the probable dominant object that created the PS, as can be observed in Figures 8a and 8b.

6. THE IMPACT OF NEW SATELLITES ON LANDSLIDE DETECTION & MONITORING

The significant progress that has been made with SAR interferometry 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.

Figure 8b. The Air Canada hangar at Vancouver International Airport. The land surrounding the hangar is settling at approximately half the rate of the building, itself.

PS data are copyright of Tele-Rilevamaneto Europa srl.
Orthophotos by McElhanney Consulting Services.

Figure 8a. PS identified on a traffic direction gantry and on a pedestrian footbridge in the alluvial sediments within the City of Surrey.

PS data are copyright of Tele-Rilevamento Europa srl.
Orthophotos by McElhanney Consulting Services.

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 InSAR 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 2008, 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 phenomena, should open a completely new scenario in landslide 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. Finally, the higher spatial resolution of future SAR sensors will lead to smaller artificial reflectors than those in use today. The latter are used 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.

7. CONCLUSIONS

InSAR, and particularly the PS Technique, is a proven technology for use in analysis of terrain stability problems. It stands alone among other site investigation methodologies for its ability to offer retroactive analysis of geohazard behaviour.

With respect to its use in landslide detection and monitoring, despite the loss of coherence induced by vegetation coverage in the lower sector of the Castagnola landslide, the InSAR analysis using the PS Technique enabled retrieval of ground deformation measurement in the central part of the landslide body, where the highest level of risk is present. The InSAR measurements have shown good conformity with the findings of other site investigations, e.g. slide boundary delineation and subsurface movement, and confirm the capabilities of InSAR as an effective tool for the monitoring of ground surface deformation of slow mass movements (up to a few centimeters per year) occurring on slopes of low vegetation density.

In its broader application to other terrain instability issues, the technology has confirmed land movement trends, derived by other geophysical investigations in the upland and Coast Mountain areas of the Lower Fraser valley, in British Columbia. It has also demonstrated itself to be an effective site investigation tool in identifying local land instability challenges.

8 ACKNOWLEDGMENTS

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