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Permanent Scatterers for landslide investigations: outcomes from the ESA-SLAM project

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Abstract

Within the SLAM project (Service for Landslide Monitoring), launched in 2003 by the European Space Agency (ESA) the Permanent Scatterers (PS) technique, a multi-image interferometric approach, coupled with the interpretation of aerial-photos and optical satellite images, was carried out for landslide investigations. The PS analysis was applied at a regional scale as support for landslide inventory mapping and at local scale for the monitoring of single well-known slope movements. For the integration of the PS measurements within a landslide inventory the Arno river basin (Italy) was chosen as test site for the presence of a high number of mass movements (to date about 300 areas at high landslide risk and more than 27,000 individual landslides mapped by the institutional authorities). About 350 SAR images have been interferometrically processed by means of the PS technique, with the detection of about 600,000 PS. The use of optical images contributed spatial meaning to the point-wise information provided by the PS, making it easier to identify terrain features related to slope instability and the landslide boundaries. Here we describe the employed methodology and its impact in the updating of a preexisting landslide inventory. 6.8% of the total number of landslides were characterized by ground displacement measurements from the PS: 6.1% of already mapped landslides and 0.8% of new unstable areas detected through the PS analysis. Moreover, most of the PS are located in urban areas, showing that the proposed methodology is suitable for landslide mapping in areas with a quite high density of urbanization, but that over vegetated areas it still suffers from the limitations induced by the current space-borne SAR missions (e.g. temporal de-correlation). On the other hand, the use of InSAR for the monitoring of single slow landslides threatening built-up areas has provided satisfactory results, allowing the measurement of superficial deformations with high accuracy on the landslide sectors characterized by a good radar reflectivity and coherence.

Keywords: Space-borne SAR interferometry; Permanent Scatterers; High resolution satellite imagery; Landslides; Monitoring

1. Introduction

Landslides represent one of the most diffuse and problematic natural hazards in many parts of the world, threatening urban areas, human activities and cultural heritage, thus influencing the socio-economic conditions of many countries (Schuster, 1996). Economic consequences related to landslides are difficult to estimate given the widespread occurrence of relatively small but damaging events. Landslide impact for the Italian territory has been well addressed by the statistical analysis of the data collected in recent years by the GNDCI (National Group for Geo-hydrological Disaster

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Prevention) of the CNR (National Research Council) (Guzzetti, 2000). The total amount of damage caused by landslides in Italy in the last century has been evaluated at €1–2 billion/year, corresponding to about 0.15% of the national gross domestic product. In the same period there have been 59 deaths/year due to mass movements.

In order to keep an adequate safety level, especially in those situations where relevant property and infrastructure are exposed, a thorough understanding of landslide distribution and state of activity is mandatory. Conventional methods used for mapping and monitoring slope instabilities could benefit from the use of remote sensing systems, which allow rapid and easily updatable acquisitions of data over wide areas, reducing field work and costs. Although several attempts at employing space-borne remote sensing techniques for this purpose have been carried out in recent years, especially in the optical region of the electromagnetic spectrum (Mantovani et al., 1996; Hervas et al., 2003; Metternicht et al., 2005), the use of such data has rarely been successful. This is because most space-borne sensors provided insufficient spatial resolution until very recently. Several examples of applications of satellite SAR interferometry (InSAR) to landslide investigations are also available in the scientific literature (Achache et al., 1995; Fruneau et al., 1996; Carnec et al., 1996; Singhroy et al., 1998; Rott and Siegel, 1999; Rott et al., 1999; Kimura and Yamaguchi, 2000; Refice et al., 2000; Singhroy and Mattar, 2000; Berardino et al., 2003; Singhroy and Molch, 2004; Catani et al., 2005; Strozzi et al., 2005; Corsini et al., 2006), but the results have been conditioned by strong limitations for a systematic and generalized use. The main drawbacks relate to the acquisition parameters of the current space-borne SAR missions (e.g. incidence angle, revisiting time interval, and spatial resolution), not properly suited for slope movement detection and monitoring.

As a result, to date the most widespread remote sensing technique used for landslide mapping seems to be the visual interpretation of stereo aerial photographs, useful for recognition, classification and geomorphic characterization of mass movements (Soeters and Van Westen, 1996).

Recent advances in optical and radar satellite capabilities (e.g. high spatial resolution, stereoscopic view and high temporal frequency acquisitions), the development of new robust techniques based on the interferometric analysis of large datasets of radar images (multi-interferogram approach), such as the Permanent Scatterers (PS) (Ferretti et al., 2001) or the small baseline (SBAS) Differential SAR Interferometry (DInSAR) approach (Berardino et al., 2002), and the possibility of integrating these data within Geographical Information System (GIS) have dramatically increased the potential of remote sensing for landslide investigations.

As part of the SLAM project (Service for Landslide Monitoring) of the European Space Agency (ESA), funded within the framework of the Data User Program, a methodological approach has been developed to integrate interferometric information coming from the Permanent Scatterers analysis with the interpretation of optical images (Colombo et al., 2003a,b; Farina et al., 2004). The method relies on the possibility of assigning a spatial meaning to the point-wise ground displacement measurements provided by the PS technique, through the interpretation aerial-photos and optical satellite imagery, topographic maps and ancillary data. Due to the remote sensing character of the above approach, which allows the acquisition of data over wide areas, and the extremely high precision of the radar measurements (Colesanti et al., 2003), this method can be applied at different scales. Over large areas it is suitable to complement and integrate information derived from well-established techniques for landslide mapping and at local scale it can be used for monitoring the superficial displacements of specific landslides.

This paper presents the results obtained in the application of the proposed method to the Arno river drainage basin, Central Italy. This test site, covering a spatial extension of about 9000 km^2 and containing more than 27,000 landslides, has been selected due to its significance with respect to the Italian Apennines, in terms of landslide typologies, geological setting and climatic conditions. By working at a regional scale the whole territory of the Arno drainage basin has been analyzed in order to update an existing landslide inventory map. In addition, detailed monitoring of superficial displacements of a few well-known mass movements has been performed, aimed at evaluating variations over time of the deformation rates and spatial extents of the unstable areas. The results required strong multi-disciplinary expertise. During the project a regional institution in charge of landslide risk management activities was engaged to assess the results and the impact of the proposed methodology on their current practices.

2. Study area

This study describes results from the Arno river drainage basin. This area, with a spatial extension of 9131 km^2 and a mean elevation of 353 m a.s.l., is located in Central Italy, along the Central-Northern Apennine (Fig. 1). 55% of the territory has an elevation lower than 300 m a.s.l., 30 % between 300 and 600 m a.s.l., 10 %

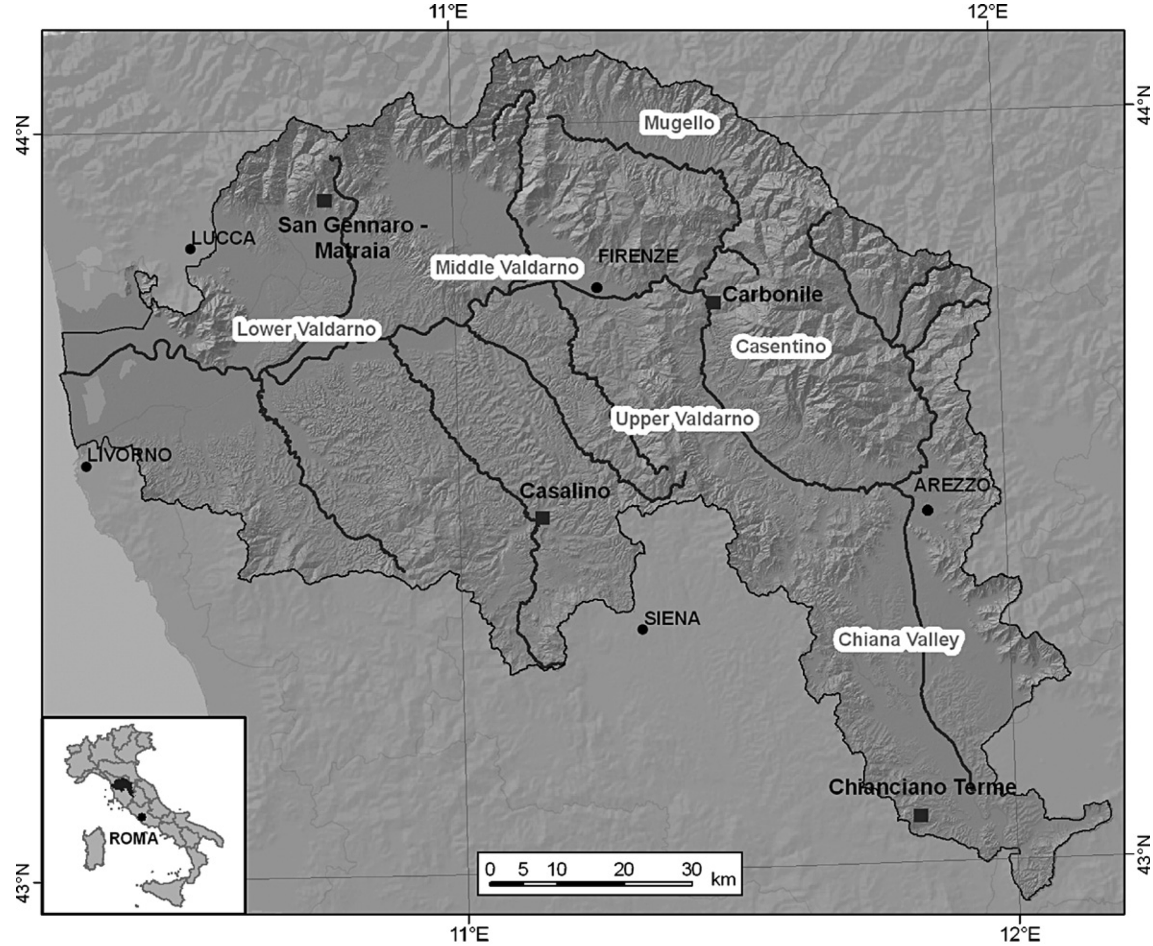

Fig. 1. Location map of the Arno River basin, Italy (inset).

between 600 and 900 m and less than 5 % is higher than 900 m a.s.l.. Forest covers 3500 km^2, while farmland covers 4315 km^2. From a geological and climatic point of view the area can be considered quite homogeneous, being located within the Apennine mountain belt. The outcropping terrains belong mainly to arenaceous and calcareous turbitidic sequences and argillaceous units characterized by a chaotic setting of sedimentary and tectonic origin. Such a geological setting, combined with the high relief of the area and with the meteorological conditions, typically characterized by intense rainfall periods concentrated during fall and spring, has made the Apennines susceptible to landslides. The Arno river Basin Authority (Autorità di bacino del Fiume Arno, AdBA), the public institution remitted by the Italian law to oversee hydro-geological risk management within the Arno river territory, mapped more than 27,000 landslides. These directly affect more than 16,000 civil buildings, 460 industrial areas and 350 km of roads. The landslide inventory map produced by the AdBA for the hydro-geological risk management plan (Piano per l'Assetto Idrogelogico, P.A.I., http://159.213.63.82/sitopai/carte/portale_pai/html/pai.html) indicates that the rotational and planar slides represent 74% of the total mass movements, solifluction and creep account for 19%, about 5% are represented by flows and the remaining 2% of mass movements result from deep-seated gravitational slope deformations. Most of the slope movements, especially the slides, are reactivations of pre-existing phenomena that originally occurred in periods characterized by different climatic conditions. Intense rainfall and snowmelt, as well as anthropogenic activities, in particular agricultural practices, are identified as the main triggering factors for the reactivation of these dormant landslides (Canuti et al., 1979).

From a kinematic point of view the majority of the landslides are slow and intermittent, with accelerations in correspondence of prolonged and intense rainfall (Canuti and Focardi, 1986). With reference to the classification scheme proposed by Cruden and Varnes (1996), recorded deformation rates range between extremely slow to moderate.

Such a dense spatial distribution of mass movements, combined with a high population density (2,581,369 residents distributed over 166 municipalities) create high risk conditions related to landslide occurrence. In fact, more than 300 areas are considered at high risk from landslides in the P.A.I. maps, due to the combination of high values of landslide hazard, elements at risk and vulnerability. A few of these sites have been selected, in collaboration with the AdBA, as test areas for the satellite-based monitoring. The choice was based on the exposure to the satellite line of sight (L.O.S.) of the sites, their average deformation rates, compatible with InSAR capabilities, and the availability of in-situ data for validation activities.

3. Datasets and methods

The proposed methodology relies on the combination of ground displacement measurements provided by SAR interferometry with the visual interpretation of aerial photos and optical satellite images. Optical imagery is necessary for the detection of diagnostic morphology created by mass movements in order to distinguish landslides from deformation related to subsidence, structural settlement of buildings, and the swelling of clayey terrains.

Typologies and main characteristics of the remote sensing data employed in this study are briefly summarized in Table 1.

Table 1
Summary of the remote sensing data employed for the study

Type of data	Source	Temporal acquisition	Spatial coverage	Ground resolution or pixel size (m)
Radar images	ERS1-ERS2	From 1992 to 2002	Whole basin	25
Optical images	Foto AIMA B and W orthophotos (digital)	1996	Whole basin	Approx. 1
	Volo ITALIA color orthophotos (digital)	2000	Whole basin	Approx. 1
	Stereoscopic B and W aerial photos (printed)	1993–1995	Whole basin	1–3
	SPOT5	03/2003	3600 km^2	5
Topographic maps	CTR (1:10,000 scale)	2002	Whole basin	–
Digital elevation models (DEM)	Derived from CTR	2002	Whole basin	10

3.1. SAR dataset and interferometric processing

A dataset of SAR images acquired by the ERS1 and ERS2 satellites was collected from the ESA archive. To limit the effects of geometrical distortions induced by the side-looking view of SAR sensors, data acquired both from ascending and descending orbits were selected over the whole territory of the Arno river drainage basin. More than 350 scenes were acquired, spanning from 1992 to 2002. Such a large amount of SAR data was necessary to perform the Permanent Scatterers processing (PSInSAR) (Ferretti et al., 2000, 2001). This interferometric configuration, developed at the Politecnico di Milano (POLIMI) and based on the analysis of a large dataset of SAR images (at least 20–25 scenes), overcomes the main drawbacks of conventional differential SAR interferometry (DInSAR) for ground displacement retrieval. Temporal decorrelation due to vegetation coverage dramatically affects interferometric coherence, with the effect of obtaining good results only for urban areas or bare rock. In addition, atmospheric components of the interferometric phase, which cannot be estimated when using only two SAR scenes, only permit a centimetric precision of the ground displacement measurements. For these reasons, with conventional DInSAR, reliable results can be obtained only in the case of large landslides that occur on gentle slopes (generally less than 20–30°) and in sparsely vegetated environments. Permanent Scatterers processing over the whole dataset of SAR images only takes into account pixels with high quality signal levels, in terms of amplitude and coherence values, and identifies individual radar benchmarks called Permanent Scatterers (PS), where accurate deformation measurements can be carried out. PS usually correspond to man-made structures, as well as natural reflectors, such as exposed rock that can be identified with a georeferencing accuracy related to the original spatial resolution of the employed SAR images (for ERS1 and ERS2 data the accuracy is about ±4 m in azimuth and ±8 m in slant range). The use of a large dataset of SAR scenes also permits the statistical evaluation and removal of the atmospheric component of the phase. This allows millimetric precision to be obtained in the displacement measurement. Two different approaches can be adopted in PS processing. The first, termed “standard”, allows the detection of radar benchmarks and estimation of their average velocity during the monitored period through an automatic procedure. A linear motion model is searched for and information about linear velocity is extracted. This approach is suitable for processing large numbers of scenes related to wide areas in a limited period of time. The results of this analysis consist of the yearly average velocity of a series of points mainly corresponding to man-made structures.

The second type of PS analysis, called "advanced", does not assume any linearity in the displacement trend and can provide the time series of displacements for each PS. The advanced analysis is a more sophisticated and time-consuming procedure (approximately three times longer than the standard one) and requires skilled personnel. Indeed, such processing limits phase unwrapping errors, allows the evaluation of the atmospheric component of the phase on a denser grid and the optimization of the dataset, by removing SAR acquisitions that could decrease the PS density (e.g. acquisitions with presence of snow, acquisitions characterized by anomalous values of soil moisture, etc.). For these reasons it is suitable for small areas, such as specific landslides, where the phenomenon has to be investigated in detail. In fact, time series of displacements enable the deformation evolution of each PS over time to be followed and the absence of an a-priori linear model results in a denser network of PS.

The PS technique has been applied to the monitoring of ground deformations induced by different natural and anthropogenic phenomena, such as tectonic motions, volcanic uplifts, land subsidence (Ferretti et al., 2000; Musson et al., 2004; Salvi et al., 2004) and in a few cases also to landslides (Colesanti et al., 2003; Colesanti and Wasowski, 2004; Hilley et al., 2004; Ferretti et al., 2005).

The standard PS analysis was employed for the whole Arno basin with the aim of mapping landslides at a regional scale. The analysis was carried out with SAR data both from ascending and descending orbits, with the processing of two different datasets, one spanning the time period from 1992 to 2002 and the other related only to a subset from 1999 to 2002. On the other hand, the monitoring of a few selected slope movements in built-up areas was carried out through the advanced PS analysis.

3.2. Optical dataset and ancillary data

As support to the ground displacements provided by the PS analysis, optical images both from airborne and space-borne sensors were acquired. To perform a multi-temporal analysis aimed at identifying existing landslides based on their topographic features as well as vegetation related indicators, two sets of aerial orthophotos acquired at 1:10,000 scale, respectively during 1996 and 1999 were collected. By overlaying the two sets within a GIS environment the visual interpretation of differences in vegetation coverage, in soil moisture (moist bare soils decrease the pixel spectral reflectance, especially in the visible-red part of the electromagnetic spectrum, resulting in darker areas on the image) and in the drainage network was employed as a complement to displacement measurements provided by the PS analysis. Moreover a set of stereoscopic aerial-photos at 1:33,000 scale acquired over the mountain sectors of the Arno river basin was used to analyze areas of particular interest, where the monoscopic approach was not able to identify diagnostic landslide features. A panchromatic SPOT5 image, covering a portion of the basin of about 3500 km^2, was also acquired and ortho-rectified. SPOT5 data were selected to test their applicability compared to the acquired conventional aerial imagery for landslide identification and classification. Although the spatial resolution of the image (5 m) is still not comparable with that of aerial photos, the larger spectral band and the 11-bit digital format can provide good results in mass movement detection, if the size of the phenomena and the texture contrast with respect to the surrounding areas are sufficiently large.

As additional inputs for the study a recent (10 m cell-size) Digital Elevation Model (DEM), with a nominal vertical accuracy of 5 m, and topographic maps at 1:10,000 scale were obtained for the whole Arno basin. Terrain slope and aspect maps were derived from the DEM for the interpretation of directions of ground movements measured by InSAR. In fact PS technology provides only the component of the real displacement vector measured along the satellite's line of sight (L.O.S.). In order to estimate the movement direction compatible with the PS measurements, it is necessary to combine the L.O.S. information (different for ascending and descending orbits) with the topographic features (e.g. slope and aspect). In Fig. 2 a sketch of the satellite viewing geometry with respect to the measurement of slope movements is displayed. The satellite orbit (approximately N–S) limits the technique's capabilities for monitoring landslides with N–S direction of movements. In addition, the sign of the measured displacements (positive values indicate movement towards the satellite along its L.O.S., while negative values indicate movement away from the sensor) has to be interpreted considering the terrain slope. The example of Fig. 2b explains how the same movement can be measured with different sign and magnitude by ascending and descending data.

4. Integrating landslide inventory and InSAR data

Present day landslide inventory maps have not been standardized around the world and are published at different scales with various levels of details. The most common methodologies for compiling them are based on aerial-photos interpretation, field surveys and collection of local databases (Crozier, 1984; Soeters and Van Westen, 1996). While the spatial pattern of landslides can easily be mapped using the above mentioned methods, with the exception of rugged and forested areas where the forest canopy often hides small-size failures (Brardinoni et al., 2003), the assessment of landslide state of activity is more problematic. Several attempts for the discrimination between active and dormant landslides through aerial-photo interpretation have been made (Wieczorek, 1984; Gonzalez-Diez et al., 1999), also on the basis of multi-temporal aerial-photo interpretation (Canuti and Focardi, 1986). However, the state of activity of dormant landslides mostly covered by vegetation and characterized by topographic features not clearly related to slope instabilities can be difficult to recognize even through multi-temporal aerial-photo interpretation. Space-borne SAR interferometry can make a valuable contribution to this issue at least where a few strong reflectors are available within the landslide body. Here we propose the integration within a pre-existing landslide inventory map, produced with conventional geomorphologic tools, of ground displacement measurements over a sparse grid of points provided by the PS analysis.

The main benefits of this analysis relate to a better definition of boundaries of already detected mass movements or of their state of activity and to the detection of previously unknown unstable areas. However, although this methodology represents a promising tool for landslide investigations, many challenges may limit its applicability. The main controlling factors that hamper the reliability of the methodology are represented by the need of the presence of buildings or man-made structures within the unstable area, which limits reliable results to urban or peri-urban areas, and the possibility of measuring only displacements of up to 4–5 cm/year with C-band data (e.g. ERS1/2 and Radarsat data) due to problems induced by the intrinsic ambiguity of the interferometric phase (related to its 2π module).

4.1. Application of the method to the Arno drainage basin

The AdBA produced an inventory map of active, dormant and inactive landslides at a reference mapping scale of 1:10,000, dating back to 2003 (Fig. 3). The map follows the landslide classification and the terminology proposed by Cruden and Varnes (1996), with a few slight changes due to the scope and to the extent of the analyzed basin. In particular, active landslides (moving at the time of the investigation) and suspended ones (active within the last annual cycle of seasons but were not moving at the time of the investigation) were grouped and defined as “active” because of difficulties

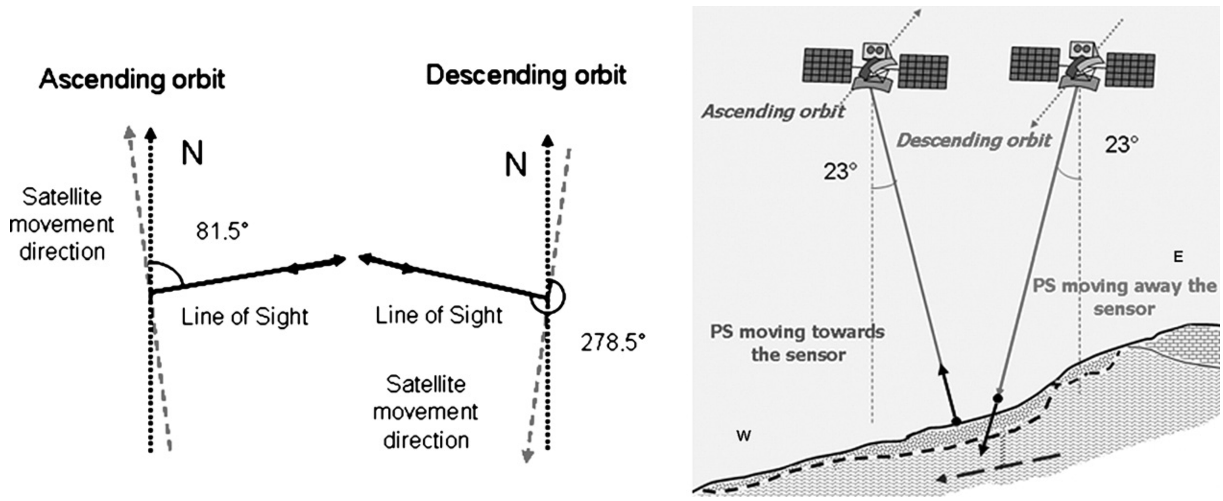

Fig. 2. Sketch of ERS1-ERS2 viewing geometry: (a) planimetric view of the sensor acquisition geometry. From this scheme limitations regarding the possibilities of measuring movements along the N–S direction are highlighted; (b) vertical view of the acquisition geometry with respect to E–W slope movements. Due to the satellite line of sight (L.O.S.), which is not vertical, the same down-slope translational movement can be recorded by descending acquisitions as a PS moving away from the sensor, while by ascending orbits as a PS moving towards the sensor with a lower modulus (a lower component of the real displacement vector is measured).

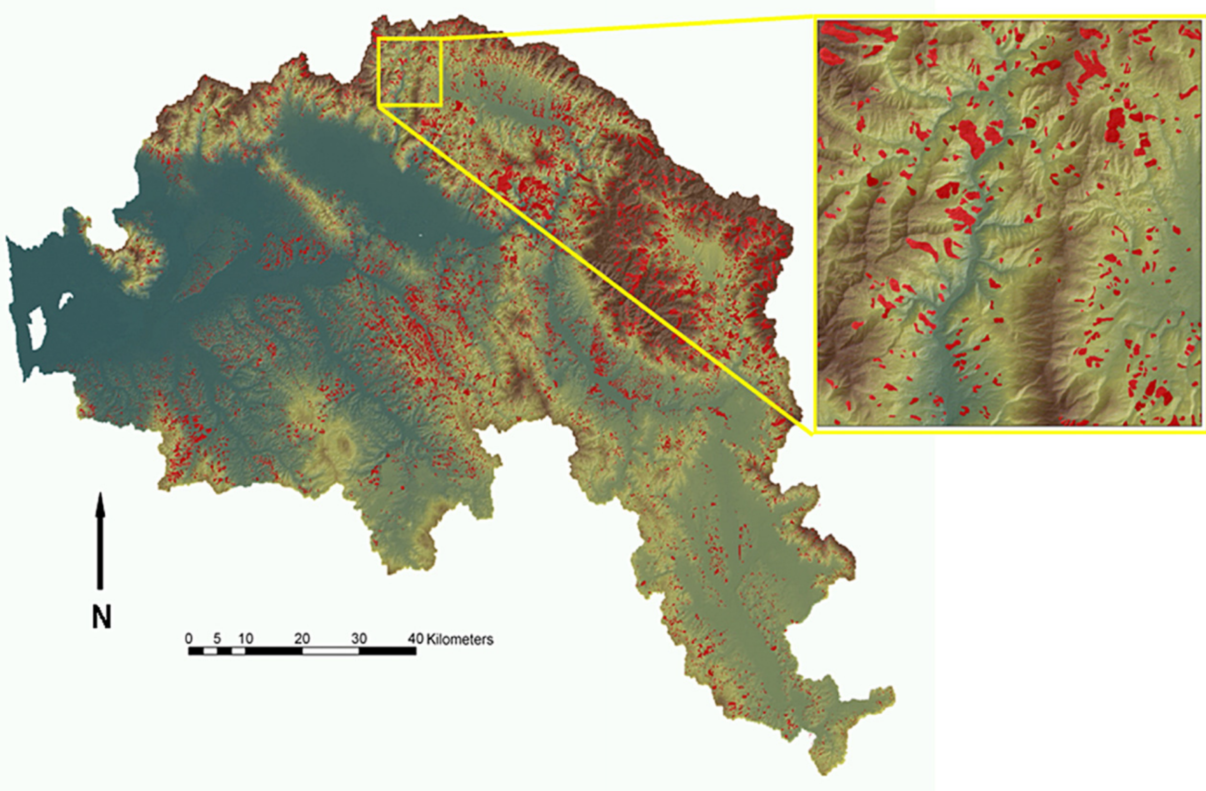

Fig. 3. Landslide inventory map of the Arno basin (2003). Landslides are displayed in red. The map, produced by the Arno Basin Authority, was compiled through aerial-photo interpretation and field surveys.

in distinguishing the two states of activity. The inventory was compiled through the analysis of available references and previous investigations carried out by local municipalities for urban planning purposes, aerial photo interpretation at different scales and field surveys for the final validation of the produced map. The resulting product consists of a digital map showing several attributes related to landslides (landslide typology, state of activity, presence of in-situ investigations and sources of information: photo-interpretation, field checks, pre-existing investigations, etc.

In total, over the area covered by the landslide inventory map 350 ERS1 and ERS2 images were processed through a standard Permanent Scatterers analysis. The results of this analysis are summarized in Table 2 and shown in Fig. 4. Although the density of PS is significantly lower in the hilly and mountainous areas (37 as opposed to 65 PS/km^2 for the overall basin area), it seems to be high enough with respect to the landslide density (3.8 landslides/km^2 in the hilly and mountainous portions, corresponding to an areal frequency of 11.2%).

InSAR data were integrated within the inventory map in a GIS environment. For each municipality, the PS were overlaid upon the pre-existing landslide inventory in order to evaluate main differences in terms of spatial distribution and state of activity of landslides with respect to InSAR measurements. The first effort was devoted to the detection of the presence of PS within or close to mapped mass movements. Where the inventory information was in agreement with the PS data (both boundaries and state of activity) the average velocities of Permanent Scatterers located within the landslide, computed on the two different time intervals (1992–2002 and 1999–2002), were added as new fields in the attributes table. In case of differences in the spatial distribution, e.g. PS in movement close to the landslide boundaries, or in the state of activity, e.g. PS stable within an active landslide, the support of multi-temporal aerial-photos or SPOT5 image was employed. The interpretation of these data was aimed at detecting morphological or vegetation features indicative of a variation of the landslide boundaries or a change of its state of activity. In Fig. 5 an example of such a case is displayed. The figure shows changes related both to boundaries and state of activity. The majority of buildings located in the upper part of the landslide

Table 2
Summary of the PS analysis on the whole Arno basin territory and on the mountainous and hilly areas of the basin (above slope values of 3%)

Area of Arno river basin (km^2)	9131
Mountainous and hilly area (km^2)	7190
PS in the whole Arno river basin	
No. of PS	591,263
No. of PS ascending orbits	263,321
No. of PS descending orbits	327,942
PS density tot (PS/km^2)	64.75
PS asc. orbits density (PS/km^2)	28.84
PS desc. orbits density (PS/km^2)	35.91
PS in hilly and mountainous areas	
No. of PS	265,177
% on whole No. of PS	44.8%
No. of PS ascending orbits	82,607
No. of PS descending orbits	182,570
PS density tot (PS/km^2)	36.88
PS asc. orbits density (PS/km^2)	11.49
PS desc. orbits density (PS/km^2)	25.39

mapped by the AdBA records a stable behavior during the monitored period (displacement rates around −1 and 1 mm/year along the L.O.S.). Only in correspondence of a few buildings, located in the detachment zone, radar benchmarks show higher displacement rates, with values of up to 5 mm/year, which can be correlated to the slope movement. As a consequence the boundaries have been slightly modified and the phenomenon, initially classified as dormant by the AdBA, was reclassified as active, assuming that displacements in the upper part of the landslide are significative of the state of activity of the entire landslide. A field check allowed the identification of several cracks in the buildings corresponding to PS in movement.

Furthermore, a strong effort was spent on the interpretation of moving PS located far from any mapped landslide. To limit possible misinterpretations, attention was focused only on groups of PS characterized by displacement rates (over 3–4 mm/year) that are significant with respect to the technique precision. Sparse radar benchmarks showing lower rates were neglected. The support of photo-interpretation and contour lines analysis for detecting diagnostic morphologies induced by slope instabilities was fundamental at this phase, as were field surveys for particularly problematic areas.

For this type of analysis the use of SPOT5 data provided good results only in a few cases over large landslides, having a spatial extension at least of 0.1–0.2 km^2.

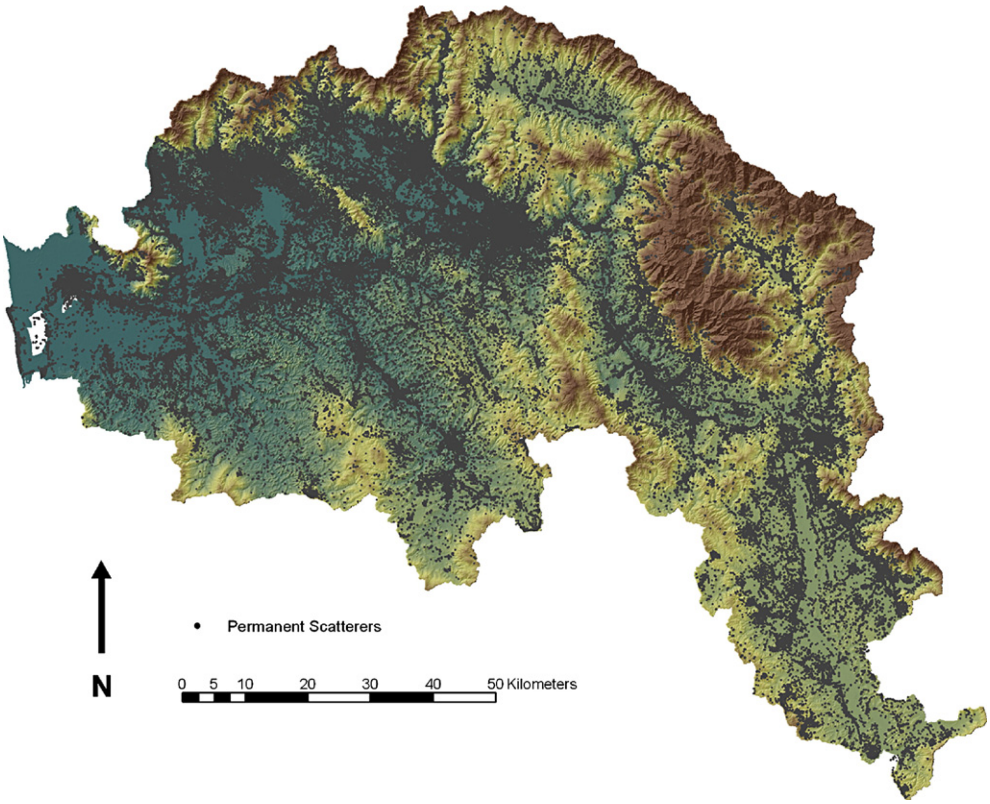

Fig. 4. Spatial distribution of the Permanent Scatterers (gray dots) over the Arno river basin.

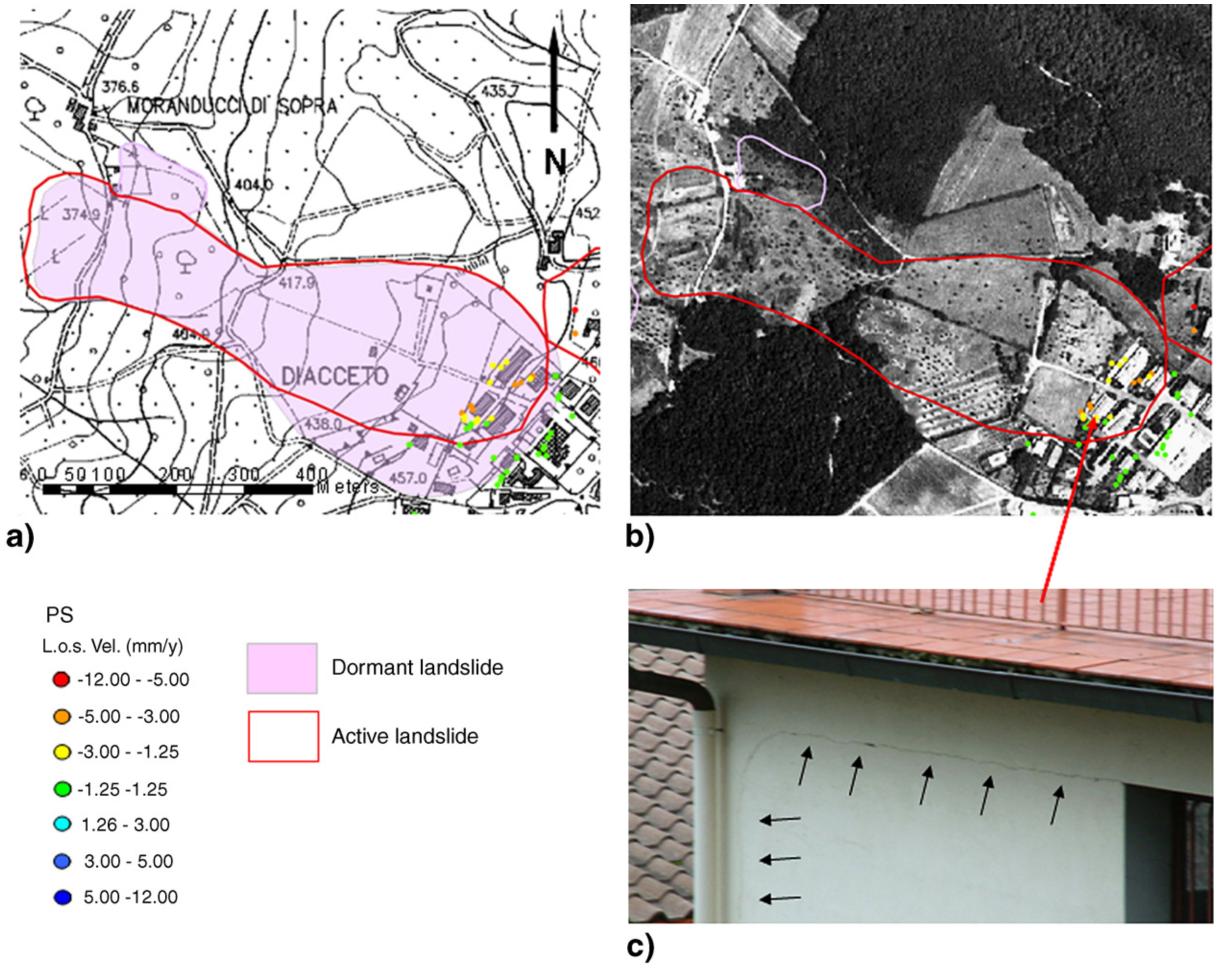

Fig. 5. Example of landslide inventory map modification with the PS-based methodology: (a) the pink polygon represents the originally mapped landslide while the red outline indicates the updated boundary from the PS method; (b) the aerial-photo (1996) of the mapped landslide; (c) cracks on a building located within the unstable area, where the PS record velocities up to 5 mm/year.

The average detectable size of mass movements was also linked to the level of contrast between the landslide body and the surrounding area.

The main problems with the analysis were related to difficulties in discriminating ground deformations due to other processes, such as natural soil compaction, settlement of man-made structures or swell of clayey terrains. For this reason only cases characterized by superficial evidence of slope movements, linked to their topography (scarps, bulges, steps, etc.) and vegetation related indicators (disrupted texture of vegetation, bent trees, etc.) were taken into account.

In order to highlight the percentage of information coming from the proposed methodology and to also evaluate its effectiveness, a simple statistical analysis of the final landslide inventory map was performed, whose results are summarized in Table 3. In the hilly and mountainous portions of the basin, 6.1% of the originally mapped landslides (the ones from the AdBA inventory) have PS information, while the number of new mapped landslides is 223, corresponding to 0.8% of the total. The end users, which were involved in the validation activities, mainly consisting of field surveys to check the ground evidence of movements measured from satellite, expressed favorable remarks on the contribution of the method to limiting uncertainties in the interpretation of slope movements over urban areas. Urban fabric usually hampers the detection of landslide indicators and the sole presence of damaged buildings does not represent univocal proof of landslide activity, especially in seismic regions, such as the Apennine territory. Moreover PS data were helpful to manage requests of modification of landslide hazard zonation from local authorities (Menduni and Sulli, 2005).

Table 3
Statistical data about the results of PS-methodology applied on the Arno basin landslide inventory map (AdBA is the acronym of Autorità di Bacino del F. Arno)

Landslides in the whole Arno river basin	
Number of landslides mapped by AdBA	27,270
Number of landslides mapped by AdBA with PS information	1664
% for number of landslides mapped by AdBA with PS information	6.1%
Area of AdBA landslides (km^2)	802.9
Area of landslides mapped by AdBA with PS information (km^2)	151.3
% of area of landslides mapped by AdBA with PS information	18.9%
Landslide density (km^2/km^2 as percentage of whole river basin)	8.8%
Landslides in hilly and mountainous areas	
Number of landslides mapped by AdBA	27,232
Number of landslides mapped by AdBA with PS information	1660
% for number of landslides mapped by AdBA with PS information	6.1%
Area of AdBA landslides in mountainous and hilly areas (km^2)	802.7
Area of landslides mapped by AdBA with PS information (km^2)	151.3
% of area of landslides mapped by AdBA with PS information	22.1%
Landslide density (km^2/km^2 as percentage of mountainous and hilly area)	11.2%
Number of new landslides mapped by the PS-methodology	223
% on number of landslides in hilly and mountainous areas	0.8%
Total number of landslides with information from PS-methodology	1883
% on total number of landslides in final inventory map	6.8%

Further work, still in progress, has the aim of analyzing the updated landslide inventory over subsets of the Arno river basin with homogeneous physiographic features. It will analyze the results of the methodology on different land uses and lithologies, assessing the impact of the main parameters which control the PS density.

5. Landslide displacement monitoring

The measurement of superficial displacements induced by a slope movement often represents the most effective method for defining its behavior, allowing the observation of response to triggering factors and the assessment of effectiveness of corrective measures. As a consequence, this type of information can be useful in predicting the phenomenon's future evolution, especially for those cases that involve high value elements at risk. Different techniques for the measurement over time of superficial ground displacements are available, from traditional extensometers and topographic surveys, up to more recent applications, such as GPS, aerial photogrammetry and LIDAR measurements (Angeli et al., 2000; Gili et al., 2000; Kaab, 2000; Hervas et al., 2003; McKean and Roering, 2004). SAR interferometry has also been applied for the retrieval of the ground displacement field of several slope instabilities, both from satellite, as reported in the introduction, and ground-based systems (Tarchi et al., 2003a,b; Antonello et al., 2004).

The InSAR technique, by providing an accurate measurement of ground displacements without the necessity of positioning any targets on the ground and without any physical contact with the slope, is best suited for assessing the temporal evolution of slow landslides (up to a few centimeters per year). Unfortunately, incidence angle, spatial resolution, wavelength, and revisiting time interval of the operational sensors are not optimal compared to the particular spatial and temporal pattern of all the types of movement we are dealing with. Moreover, the great variability of slope instabilities, in terms of mechanisms of movement, material involved, vegetation cover and size of the unstable area hampers the applicability and quality of InSAR ground displacement measurements (Colesanti and Wasowski, 2004).

Within the present study the technique was applied to four well known landslides threatening built-up areas in the Arno river basin: Casalino, Chianciano Terme, San Gennaro-Matraia and Carbonile (Fig. 1). The sites were selected according to AdBA interest in assessing the effectiveness of the adopted mitigation countermeasures or to compare the PS measurements with data acquired by in-situ instrumentation. The methodology was successfully applied to 3 of the 4 selected sites, providing us with detailed information about the landslide distribution of activity and displacement rates consistent with the ones inferred from in-situ measurements. For Casalino, Chianciano Terme and Carbonile spatial PS densities respectively of 975, 476 and 114 PS/km^2 and displacement rates of up to 15 mm/y along the satellite L.O.S. were recorded. On the other hand, the low number of PS over the San Gennaro-Matraia area (14 PS/km^2), resulted in too few ground displacement measurements hampering a reliable geological interpretation of the slope movements. The results for the Carbonile landslide are described in the next paragraph.

5.1. The Carbonile test area

Carbonile, a small village close to Pelago (Firenze) (Fig. 1), has been affected by different slope instability problems since 1984. These movements have seriously endangered the village and its 200 residents. Carbonile is located on the accumulation of a relict slide, which probably caused the deviation of the Arno river channel. Damage to cultivated areas, buildings and infrastructures have been recorded since 1984. For these reasons the whole zone was mapped as exposed to the highest landslide hazard level within the P.A.I. document by the AdBA.

The first activation of the instability problems occurred in the middle of the village during 1984 at the end of intense and prolonged rainfall and caused the evacuation of several buildings. After the event mitigation works were carried out, mainly consisting of retaining structures, drainage systems and slope reinforcements. In addition, a monitoring system with about 30 inclinometric tubes, some of which were equipped with piezometers, was set-up. The data acquisition was carried out from 1987 to 1996.

The landslides correspond to complex movements dominated by earth-slides with translational and rotational components occurring on multiple shear surfaces and with non-uniform distribution of velocities. The inclinometric readings show displacement rates ranging from slow to very slow (IUGS/WGL, 1995). Besides these phenomena, within the body of the relict landslide other instability processes are present, such as accelerated erosion, quite widespread especially to the SW of the Carbonile village.

The landslides take place in the Sillano Formation (Upper Cretaceous–Lower Eocene) which consists of shales with calcareous and marl layers, sandstones and marls characterized by a chaotic stratigraphic setting and the Pietraforte Formation (Turonian–Senonian). The latter is composed of alternating calcareous and quartzose sandstones. The presence at the top of the slope of the Pietraforte terrains, highly permeable due to their intense jointing, has been indicated as one of the

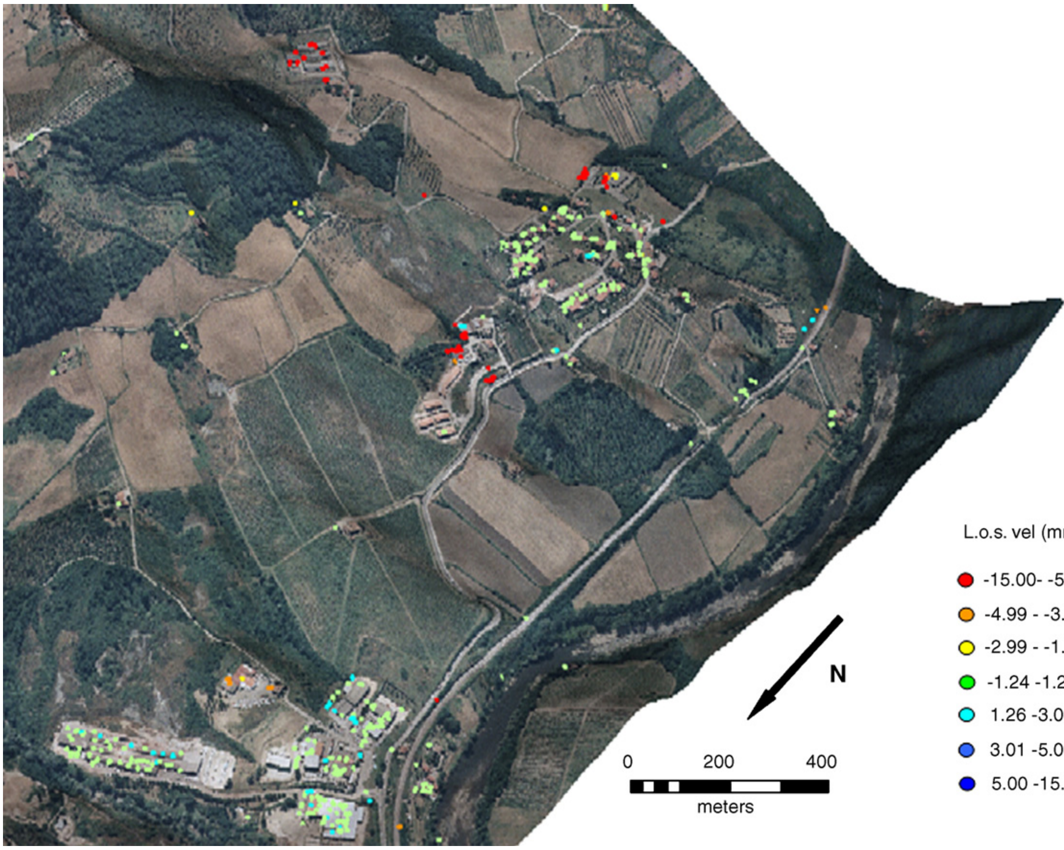

Fig. 6. Aerial-photo of the Carbonile landslide rendered on a Digital Elevation Model with the location of the Permanent Scatterers. The colors of the PS are related to the average annual velocity along the satellite line of sight, estimated between 1992 and 2002. Negative values indicate movement towards the satellite, while positive values indicate movement away from the satellite.

main landslide predisposing causes. In fact, this formation acts as water reservoir and during prolonged periods of rainfall drains a great amount of water towards the clayey materials, in the lower portion of the landslide body, rising the water table and reducing material shear strength. In addition, anthropogenic activities related to agricultural practices have modified the superficial drainage network, causing anomalous water accumulations in the ground.

The advanced PS processing performed on the ERS1-ERS2 descending dataset has allowed the detection of 310 radar benchmarks within the study site (2.7 km^2) resulting in a PS spatial density of 114 PS/km^2. The PS spatial distribution, as displayed in Fig. 6 where PS are visualized on the aerial photo rendered on the DEM, is clearly correlated to the presence of buildings, train rails and the road guard-rails. The PS velocities indicate that the central part of the ancient landslide is stable, while three zones, two on the sides of Carbonile and one in the upper part of the slope, are characterized by significant movements, with deformation rates up to 12 mm/year.

The main benefit from the interferometric analysis was the possibility to check the effectiveness of the remedial measures adopted in the last 20 years. A map, produced by the geological consultants of the municipality, reporting the main mass movements classified on the basis of their state of activity and the remedial measures carried out, was compared with the PS distribution (Fig. 7). The stability conditions of the central portion of the village, as reported by the map, are confirmed by the PS monitoring. This area benefited from the drainage works put in place at the end of the 1980s upslope of the village, consisting of a network of 5 m deep trench drains, each one 1200 mm in diameter, filled with free-draining materials (coarse-grained fills and geotextiles) and connected by collecting ditches. On the other hand, radar measurements acquired over the southern part of the village, known as “Frantoio”, detected ground displacements in areas not considered unstable by the AdBA technicians. In particular, more than 10 PS recorded movements, with an average velocity of 4.5 mm/year, which can be interpreted as a downslope movement or as a ground settlement induced by the landslide activity. PS data allowed us to also confirm the effectiveness of the adopted remedial measures. In fact, 4 parallel lines of sheet piles, ranging from 50 to 150 m in length and with piles 15 m long, were built at the beginning of the 1990s. Apart from a section of the slope constrained between two sheet pile structures, where the remedial works are not entirely effective, as confirmed by inclinometric and radar measurements and by the presence of recent cracks on a building (Fig. 7b), mitigation works made the area safer.

Another interesting site is represented by the “La Cava” area, a complex instability phenomenon mainly connected to quarrying activities. An open pit quarry of clayey materials and ground excavation induced slope instability, leading to the closure of the quarrying activity in 1964. Twenty years later, in 1984, a rotational slide with a detachment zone approximately 100 m wide suddenly occurred, producing damage to several buildings and a factory. Civil protection authorities evacuated all the houses due to the danger of continued landslide evolution. Between 1987 and 1988 mitigation works aimed at stabilizing the area were undertaken. They consist of slope regrading, a 100 m long line of sheet piles, each one 15 m deep and with a 1000 mm diameter, connected by a reinforced concrete beam. A set of deep trench drains was also constructed. The PS analysis revealed that the lower part of the slope, below the retaining structures, was moving at a rate of up to 9 mm/year along the satellite L.O.S. during the monitoring period (1992–2002). Furthermore, a few tens of meters to the N of this area, a group of radar benchmarks recorded L.O.S. velocities ranging from 4 to 8 mm/year, suggesting the persistence of instability conditions. This was confirmed by the construction between 2003–2004, a few tens of meters to the N of the described area, of a retaining structure. The structure was composed by two parallel reinforced concrete walls (Fig. 7c), built to structurally stabilize the sector of the slope where new buildings were under construction.

In order to assist the geological interpretation of the main landslides present in the Carbonile area, an integration of PS data with inclinometric readings and borehole samplings was attempted. The analysis was performed along different profiles (Fig. 8). The main rupture surfaces, placed at depths ranging from 3 to 13 m, were interpreted from the inclinometric readings, while boreholes provided the stratigraphic information. Superficial deformations are displayed along the satellite line of sight.

Profile BB (Fig. 8a) represents an example of the combined use of underground and superficial data for a better understanding of the slope instability geometry. Down-slope movements with velocities of up to 15 mm/year were recorded by the inclinometers between 1987 and 1992 (tubes 4 and 22) along a main failure surface. The PS located in the lower part of the slope also indicate ground displacements compatible with the movement measured by the inclinometer, in terms of both line of sight velocity (about 7–10 mm/year) and direction of

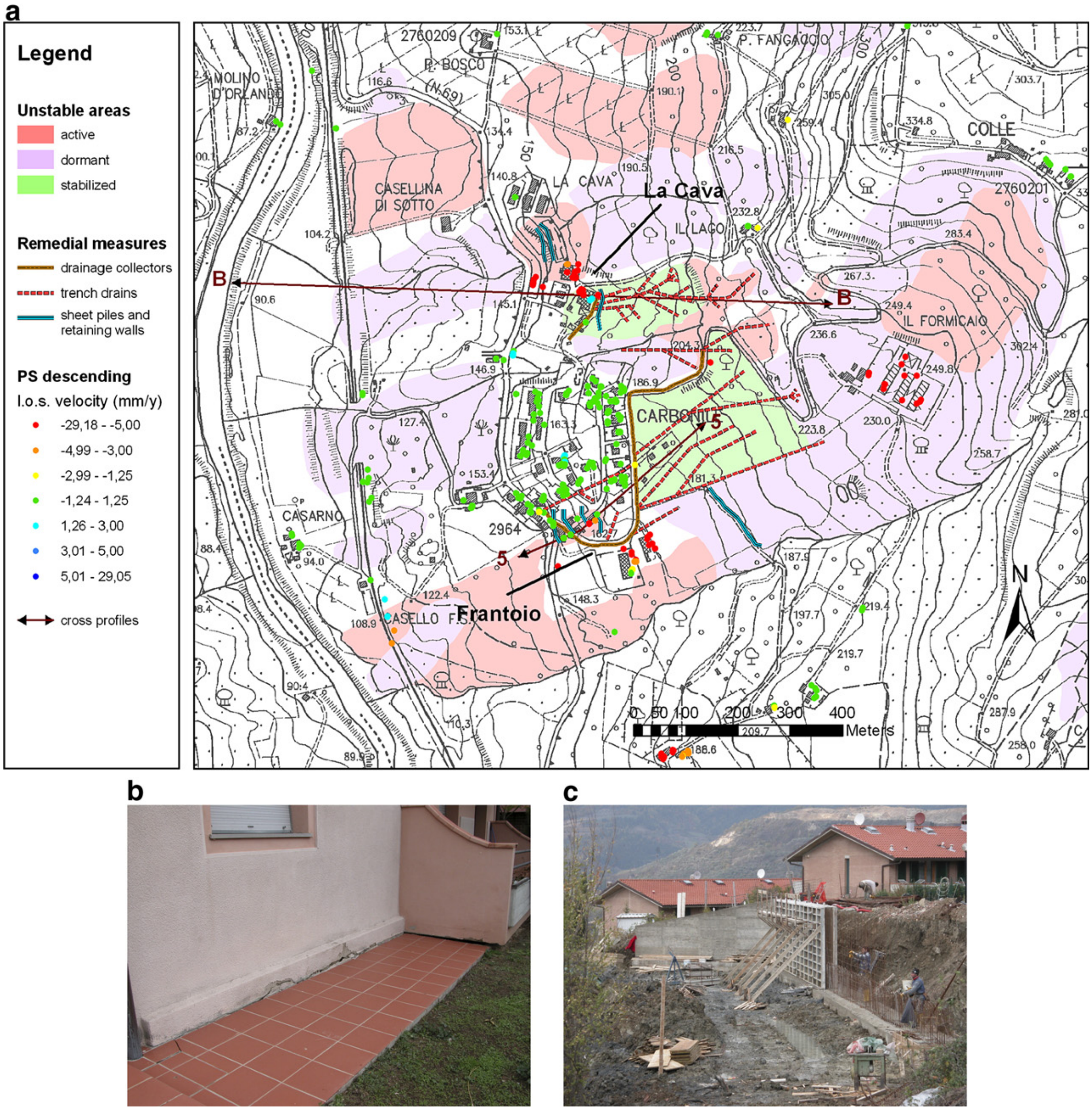

Fig. 7. a) Map produced by the Arno Basin Authority with the main unstable sectors of the Carbonile area classified on the basis of their state of activity. Also shown are the PS, the remedial measures and the location of three profiles (brown arrows). b) a damaged building in the Frantoio area. c) construction of a reinforced concrete wall in the La Cava area.

movement. The PS have negative velocities, meaning that they are moving away from the satellite sensor, which is compatible with the SW down-slope direction of movement recorded by the inclinometric tubes. Along the profile, at a distance of 700 m, two PS recorded positive velocities along the satellite L.O.S., corresponding to movements towards the satellite, that indicate ground uplift. This was interpreted as the effect of a rotational component in the slide movement of that portion of the slope, as also suggested by the local topography, characterized by an evident slope rupture at the PS location.

A quantitative comparison of PS and inclinometric measurements was performed using inclinometric tube 27 (by considering the average deformations along the tube), located along profile 5 (Fig. 8b), and the three closest PS. For the comparison the all the data were projected along the E–W movement direction recorded

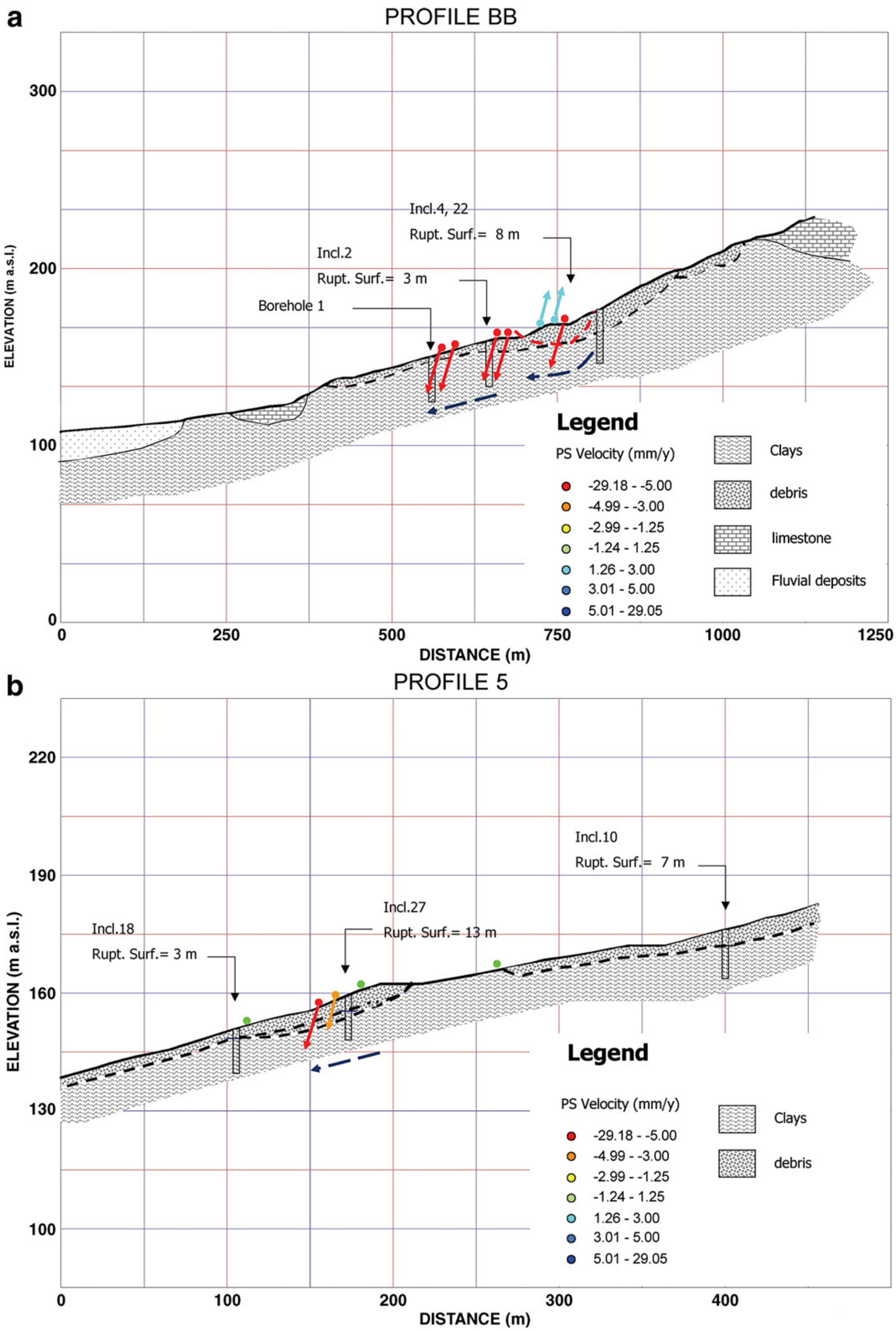

Fig. 8. Cross-sections of the Carbonile area showing both subsurface information from inclinometric readings and borehole samplings and superficial movement from the PS analysis. Dashed lines indicate the main sliding surfaces, as inferred from the inclinometric measurements. Continuous arrows represent the PS displacement vectors as measured along the satellite line of sight (L.O.S.). Arrow's length is proportional to the average PS velocity (computed over the period 1992–2002) and the vector versus indicates the velocity sign. Fig. 8a shows profile B–B and Fig. 8b profile 5–5; see Fig. 7a for profile location.

by the inclinometer, with a 10° gradient equal to local slope of the terrain. Even though the overlap in the time interval covered by the two datasets was not complete (the PS analysis ranges from 1992 up to 2002, while inclinometric readings were acquired from 1990 to 1996), the radar measurements are of the same order of magnitude as the inclinometric readings (Fig. 9). The projected average velocity (obtained from the linear fitting of the displacement measurements) recorded by the inclinometric tube between 1992 and 1996 is 3.4 mm/year, while velocities measured by the PS range from 7.0 to 13.7 mm/year, with an average value of 9.5 mm/year. The difference between the two sets of measurements was ascribed to the different types of movement measured by the two techniques (superficial vs. deep deformations) and to the low sensitivity of PS measurements to horizontal movements.

Field surveys, aimed at the identification of superficial evidence of movements, such as cracks on buildings, hummocky topography near the built-up areas, disrupted asphalt pavement along the roads and interviews of residents, were carried out together with the AdBA geologists to assess the reliability of the PS analysis. This activity allowed the AdBA to produce a revised version of the landslide hazard zonation (Fig. 10). With respect to the previous map which covered only part of the slope and where the entire urban area was classified as exposed to the maximum level of landslide hazard (PF4), the new map splits the entire slope into 3 classes (from PF2 to PF4), based on the radar measurements, evidence obtained from geomorphologic surveys and the most recently adopted remedial measures.

6. Conclusions

This research focused on a feasibility study aimed at integrating remote sensing techniques in the main phases related to landslide investigations. A methodology which takes into account the point-like ground displacement measurements coming from the Permanent Scatterers analysis and the information provided by the visual interpretation of optical images has been proposed and applied at different spatial scales. The results obtained on different test cases have been shown.

The application of this method at the regional scale, as a support for the production of a landslide inventory map, was performed on the Arno river basin, in Central Italy and shown an impact of the methodology, in terms of information regarding mass movements, on 6.8% of the total number of landslides. The percentage of already mapped landslides containing PS information is 6.1%, while new unstable areas cover 0.8%. These results can be associated with different factors. First of all the density of the radar benchmarks, which in hilly and mountainous areas reached the value of 36 PS/km^2, clearly influenced the analysis. PS density is related to land use, in particular to the density of

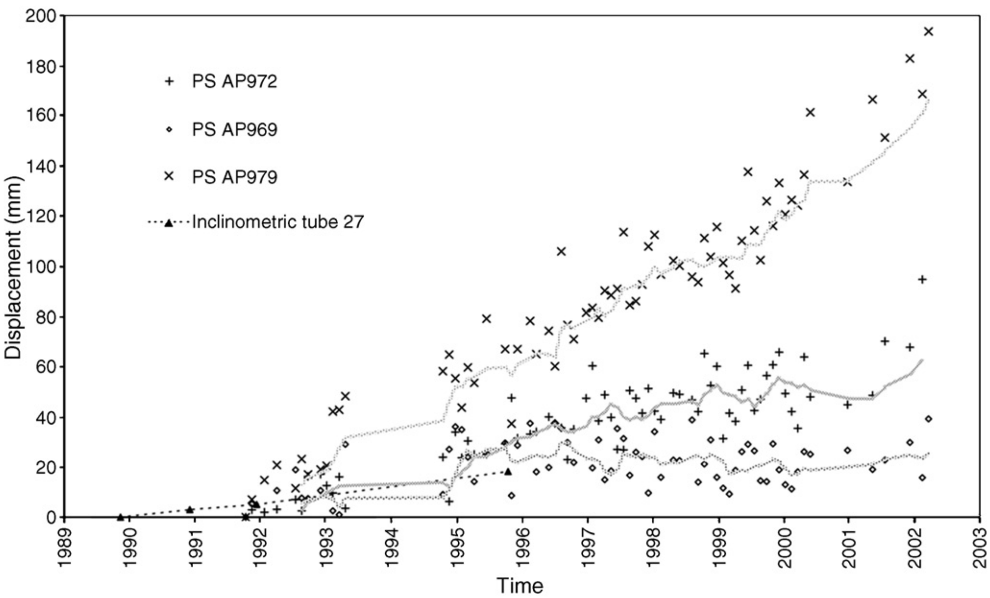

Fig. 9. Graphs displaying the displacement trends measured by inclinometric tube 27 and the nearby PS (referring to Fig. 8b: AP979 green, AP972 orange and AP979 red) spanning from 1990 to 2002. A 6 sample-moving average has been applied for the fitting of PS data.

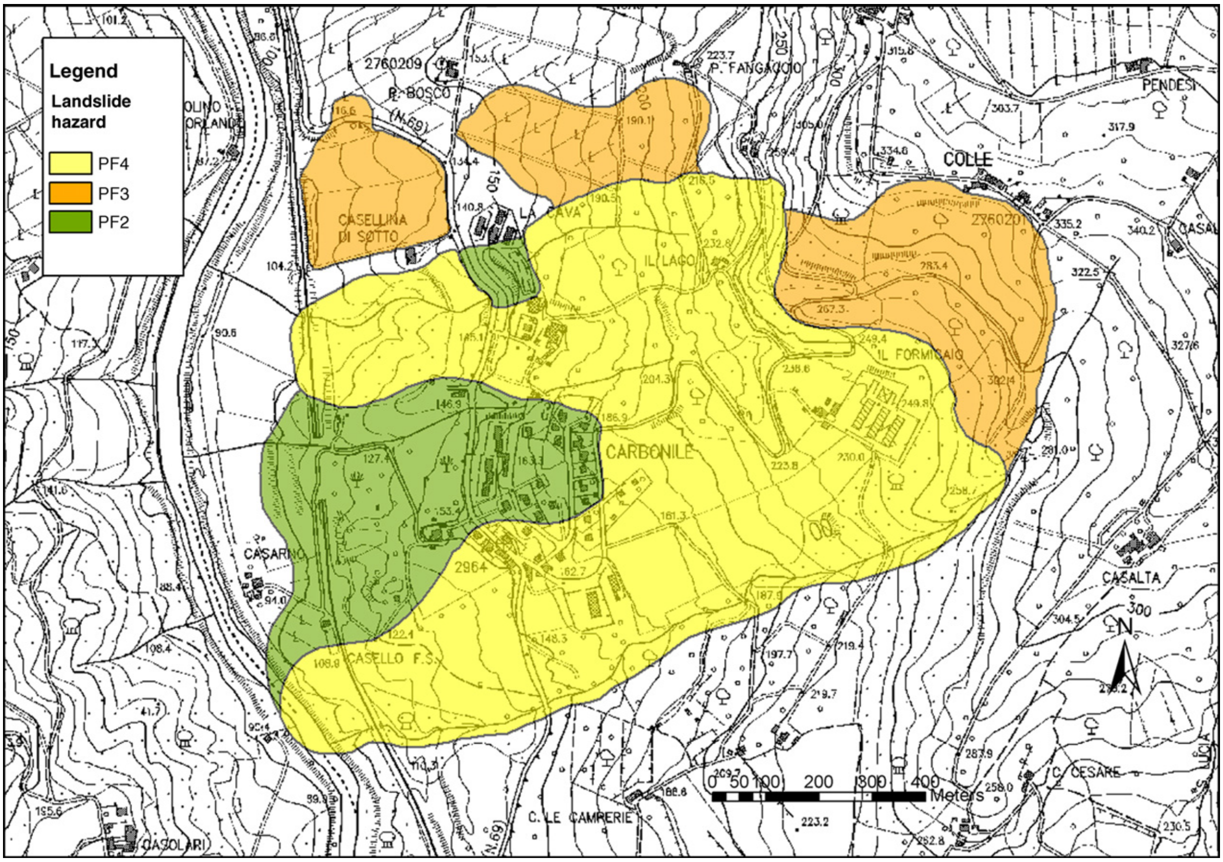

Fig. 10. Updated landslide hazard zonation of the Carbonile area (PF increases from low (2) to high value (4)), produced by the AdBA through the combination of PS measurements and field surveys.

buildings or other man-made structures, and to the average relief of the area (very steep slopes and narrow valleys induce geometrical distortions, such as layover and shadow, hampering the InSAR analysis). Furthermore, another factor to be taken into account is the typology of landslides and the related kinematics. The PS technique applied to C-band data, such as ERS1/ERS2 images, can measure displacement rates of up to a few centimeters per year. Moreover, intermittent behavior, such as that of mass movements triggered by rainfall, are difficult to detect using a linear model, as used in the standard PS analysis.

The level of acceptance of the results expressed by the end user (AdBA) has been remarkable, especially for urbanized areas, where risk conditions are usually higher. Moreover, the AdBA geologists declared to make use of the PS dataset during their fieldwork over areas where reliable conventional investigations do not exist. Thanks to the imminent launch of space-borne SAR missions with acquisition parameters more suitable for landslide investigations, within the next years the methodology could become an operational tool for landslide mapping. Indeed, future SAR missions, by providing acquisitions with a short revisiting time, such as the X-band CosmoSkyMed mission (2008), or data in L-band, such as the Japanese ALOS satellite recently launched (2006), should reduce the effect of the current limitations. The Italian–French joint initiative CosmoSkyMed, even if it will acquire data in a frequency band strongly affected by temporal decorrelation (X-band), thanks to the short revisiting time (1–2 days) and the consequent small variations of the scene's dielectric properties, will ensure very accurate displacement measurements. On the other hand, InSAR processing of L-band data, despite a lower accuracy in the provided displacement measurements, has already demonstrated its capabilities in measuring deformation rates of up to few meters per year even over vegetated areas (Catani et al., 2005; Strozzi et al., 2005).

The Carbonile results illustrated how it is possible to use Permanent Scatterers for the monitoring of single landslides inducing high risk scenarios. Superficial displacements provided by the technique are suitable for an accurate analysis of temporal and spatial displacement fields, for the creation of activity maps, and combined with other information, for interpreting the movement geometry. Moreover, the availability of images acquired since 1992 allows us to apply these data for assessing, through a non-invasive method, the effectiveness of remedial works in the monitored area. This represents a fundamental step for planning and managing mitigation activities.

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