Investigating landslide-prone towns in Daunia (Italy) with PS interferometry

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ABSTRACT: Persistent Scatterers Interferometry (PSI) and satellite radar imagery can be used to detect very slow displacements (mm-cm per year) of targets (PS) exhibiting coherent radar backscattering properties (mainly man-made structures). Here we present results of the PSI application to the Daunia Apennines, which include many hilltop towns affected by landslides. Examples from the towns Casalnuovo Monterotaro and Pietramontecorvino are used to illustrate that the interpretation of PS data on urbanised slopes can be difficult, because their movements may arise from a variety of processes: i) volumetric strains within soils, ii) natural or anthropogenic subsidence or uplift, iii) settlement of engineering structures, iv) deterioration of man-made structures, v) extremely slow slope deformations that may or may not lead to failure. Where true landslide movements are detected, they likely regard long-term post-failure displacements involving clay-rich materials.

1 INTRODUCTION

Since slope failures are a world-problem, an effective approach to landslide hazard reduction seems to be through exploitation of Earth Observation systems, with focus on long term monitoring, early detection and warning (e.g. IGOS GEOHAZARDS 2004; Wasowski *et al.*, 2007a). In particular, space-borne synthetic aperture radar differential interferometry (DInSAR) techniques are useful in landslide investigations, because of their capability to provide wide-area coverage (thousands km^2) and, under suitable conditions, spatially dense information on small ground surface deformations (e.g. Colesanti *et al.*, 2003). Furthermore, advanced multi-pass DInSAR methods such as Persistent Scatterers Interferometry (PSI; Ferretti *et al.*, 2001) and Small Baseline Subset (SBAS; Lanari *et al.*, 2004) overcome the limitations of conventional DInSAR and extend the applicability of radar interferometry from regional to local-scale engineering geology investigations of ground instability (Colesanti & Wasowski, 2006; Ferretti *et al.*, 2006). PSI techniques can be used to detect and monitor very slow displacements of targets (PS) exhibiting coherent radar backscattering properties. Since the presence of slow deformations represents evidence of potential slope failure hazard, PSI results can be used to provide a preliminary distinction between conditions of stability and instability.

However, with the exception of urban landslides, the density of persistent radar targets suitable for interferometric measurements on unstable rural and peri-urban slopes is typically low and this makes difficult PSI analysis, as well as introduces uncertainties in the assessments of true ground motions (e.g. Bovenga *et al.*, 2006; Colesanti & Wasowski 2006). Furthermore, the interpretation of the exact geotechnical significance of millimetric to centimetric yearly displacements currently detectable by PSI can be difficult, because i) such slow ground surface deformations may arise from a wide variety of causes and, therefore, their presence on slopes may not always reflect shear movements or occurrence of landslides, and ii) most radar targets correspond to man-made objects (e.g. houses) and thus their structural behaviour (and ground-foundation interactions) should be taken into account.

In this study we present the results of the application of the SPINUA PSI technique (Bovenga *et al.*, 2004) to landslide-prone towns in the Daunia Apennines (Southern Italy). We expand upon the initial works of Bovenga *et al.* (2005, 2006) by providing additional analysis of the urban areas of Pietramontecorvino and Casalnuovo Monterotaro (Fig. 1). We also focus on some difficulties in interpreting the exact origin of the PS movements detected by exploiting the European Space Agency (ESA) ERS-1/2 satellites data.

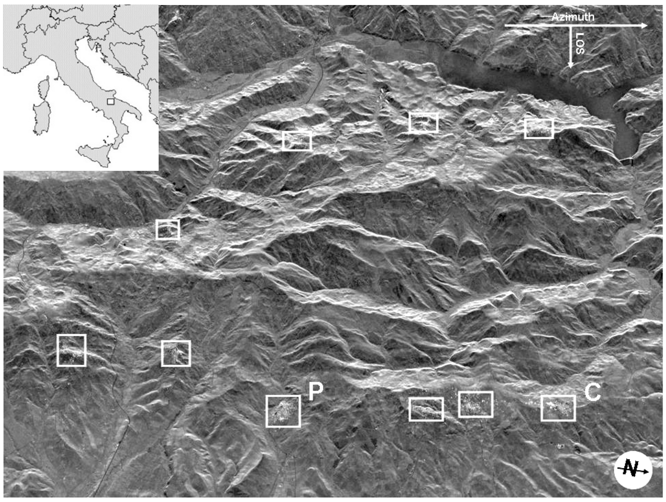

Figure 1. Filtered SAR amplitude image of the Daunia area (28 km x 27 km) showing the predominantly moderate relief hillslope topography. In addition to the towns of Casalnuovo Monterotaro (marked by C) and Pietramontecorvino (P), the white rectangles (few km in width) enclose several other towns selected for the Permanent Scatterers (PS) analysis. Inset shows location of Daunia in Southern Italy.

2 BACKGROUND ON PSI

Detailed information on PSI techniques is available in specialised remote sensing publications (e.g. Ferretti *et al.*, 2001), and its practical applicability has already been addressed in engineering geology literature (e.g. Colesanti *et al.*, 2003; Bovenga *et al.*, 2006). Here we mention only some basic aspects of DInSAR and PSI. For a recent comprehensive review of radar-based remote sensing and PSI applications for landslide assessment, the reader is referred to Colesanti & Wasowski (2006).

Space-borne synthetic aperture radars are active microwave systems capable of recording coherently the electromagnetic signal backscattered from the Earth surface. With two or more SAR images acquired over the same area during successive satellite passes it is possible to detect ground surface movements occurred between the SAR acquisitions along the Line Of Sight (LOS) direction. For the ERS satellites (incidence angle 23°), the LOS unit vector has director cosines of about 0.9 (up–down), 0.4 (east–west), and 0.05 (north–south), respectively. Thus, the maximum sensitivity is for vertical displacements.

By using C-band radar data, the detectable velocities range theoretically from about 1 mm/y up to 29 cm/y; however, recent assessments (Crosetto *et al.*, 2007) indicate that displacement rates lower than 1.5-2 mm/y and higher than 15-20 cm/y are hardly measurable in real experimental conditions.

In spite of the above-mentioned limitations, the possibility to measure, relatively quickly, deformations on slope surfaces over wide areas ($10^3 \div 10^6$ km^2), coupled with the regular update capabilities of satellite sensors, opens new perspectives in regional scale detection of slope hazards and monitoring of slow landslides (Colesanti *et al.* 2003; Colesanti & Wasowski 2004, 2006; Farina *et al.*, 2006; Hilley *et al.* 2004; Wasowski *et al.*, 2007a).

3 THE STUDY AREA

The area studied is located in the Daunia region (Southern Italy), characterized by gentle hills and low mountains, only locally exceeding 1000 m above sea level. Daunia belongs to the highly deformed area between the frontal thrusts of the Apennine chain and the western-most part of the foredeep (Dazzaro *et al.*, 1988). The chain units are characterised by a series of tectonically deformed flysch formations of pre-Pliocene age.

The clay-rich flysch units are more prone to landsliding, compared to the formations containing higher proportion of lithoid intercalations (sandstones, limestones). The widespread presence of clayey materials with poor geotechnical properties is the underlying cause of landsliding. Furthermore, as a result of the tectonic history of the Apennines, the geological materials are intensely deformed and hence also rock units are susceptible to slope movements. In general, the activity of landslides in the Daunia Apennines is characterized by seasonal remobilisations of slope movements, typically related to rainfall events. Individual meteoric events have been the most frequent triggers of landslides, even though the mean annual rainfall is modest (in the order of 600-700 mm per year).

Although mass movements appear widespread throughout the entire region (Zezza *et al.*, 1994), there are relatively few studies published on landslides in Daunia. The better documented events are concentrated within or in the immediate proximity of the urban areas. In the 1990's there has been an apparent increase in landslide activity in several urban and peri-urban areas. It is probable that the stability of slopes bordering the hilltop towns has gradually worsened because of residential development over recent decades. This has led in some cases to reactivations of pre-existing old landslides. Furthermore, the urban expansion onto marginally stable hillslopes and improper land use has led to increases in damaging first-time failures (Wasowski *et al.*, 2007b).

4 PSI ANALYSIS OF TWO TOWNS

To illustrate the potential of the PSI technique as well as current difficulties in PS data interpretation we present the results concerning two towns: Casalnuovo Monterotaro and Pietramontecorvino

(Fig. 1). These two cases are considered representative of the geologic and geomorphologic conditions encountered in other towns of Daunia.

4.1 *PSI processing*

The initial analysis (Bovenga *et al.*, 2005) involved an area of 28×27 km^2, enclosing 10 towns affected by slope instability problems (Fig. 1). We used a SAR dataset of both descending and ascending ERS-1/2 acquisitions (40 and 35 scenes, respectively) covering the period 1995-1999. The dataset was pre-processed adopting optimized solutions for co-registration, relative calibration, and resampling (see Bovenga *et al.*, 2005, 2006 for more details). The analysis was limited to small image windows of size ranging from 5 to 15 km^2 (Fig. 1). The windows enclose towns, excluding vegetated rural areas that typically contain very few PS. This strategy was adopted to ensure an adequate distribution of PS candidates needed for a reliable correction of the atmospheric signal. Such approach was also considered as most practical given that landslides with high socio-economic impact in the study area are those affecting urban centres.

4.2 *Interpretation of the PS results: the case of Casalnuovo Monterotaro*

Figure 2 shows that the great majority of PS, which falls within the built up area, results to be stable. This is not surprising as the central part of the town develops along a flat topped N-S trending ridge made of the Flysch di Faeto Formation. This Miocene age flysch, consisting of an alternation of marly limestones, calcarenites and marly clays, is relatively less prone to landsliding than the so-called Argille Bentonitiche (clay-rich unit of Miocene age including bentonite clays). The latter crop out at the eastern and western peripheries of the town (Zezza *et al.,* 1994).

There are, however, two small groups of moving PS situated in the eastern periphery of the town, on gently inclined head portion of a local valley (Fig. 2). These PS show low velocity (from –3 to –4 mm/y) movements. The negative sign stands for the displacements away from the radar sensor and, given the ascending satellite acquisition geometry, can be interpreted as indicative of either downward (subsidence) or downslope (eastward) movements, or a combination of both. The presence of moving PS in the east-facing head portion of the valley, in the vicinity of old landslide scarps, could suggest landslide origin for the detected movements. However, in cases like this, in situ monitoring data are needed to demonstrate whether the predominant displacements are indeed in downslope or vertical directions.

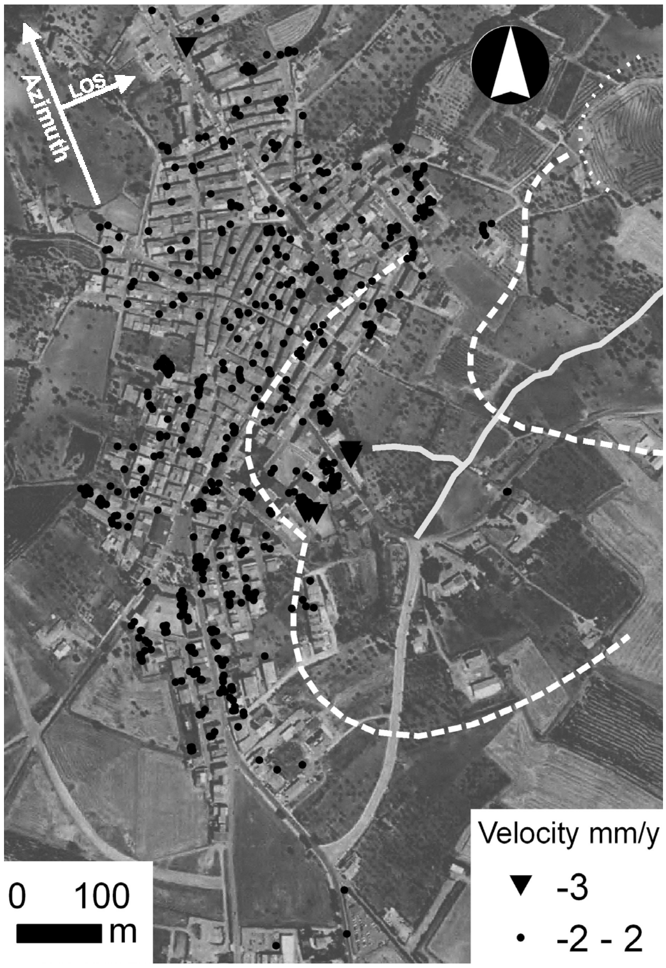

Figure 2. Distribution and average line of sight (LOS) velocity of radar targets (PS marked by black symbols) in Casalnuovo Monterotaro. Negative and positive velocities indicate, respectively, movements away from and towards the sensor; PS within the velocity range –2-2 mm/y are assumed motionless. Background image is a 1997 orthophoto. Locations of relict and recent landslide scarps (dashed and dotted white lines, respectively), are after Zezza *et al.* (1994). A small watercourse draining the valley at the eastern periphery of the town is shown in light gray. Note also ascending radar satellite acquisition geometry (white arrows).

Nevertheless, inspections of the slope stability conditions in the eastern part of the town (conducted in the recent years for the Department of Civil Protection) revealed that several buildings and retaining walls, including those with moving PS, show signs of distress and have suffered recurrent damage (cracks) since the 1990s. This confirms the reliability of the PS results. Because the clusters of moving PS are small, they probably point to local site instabilities rather than to true landslide movements. The cut and fill re-shaping of the valley head during the post-second world war development of the town has obliterated the evidence of landslide legacy, but the presence of artificial fill mantling the clay-rich slope substratum could be a cause of the local ground settlements and structure instability. Variations in local drainage conditions and in water input to the slope could also play an important role by inducing volumetric changes in the soil.

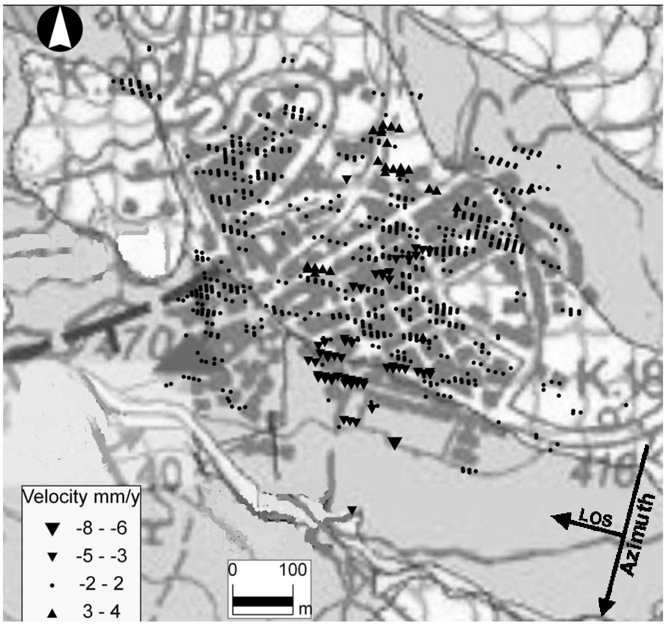

Figure 3. Distribution and average line of sight (LOS) velocity of radar targets (PS marked by black symbols) in the Pietramontecorvino area. Negative and positive velocities indicate, respectively, movements away from and towards the sensor; background geological map from http://www.apat.-gov.it: clay-rich Flysch Rosso Formation (in grey colour) of pre-Pliocene age and three old landslides (in white). General downslope direction is to SSE. Note also descending radar satellite acquisition geometry (black arrows).

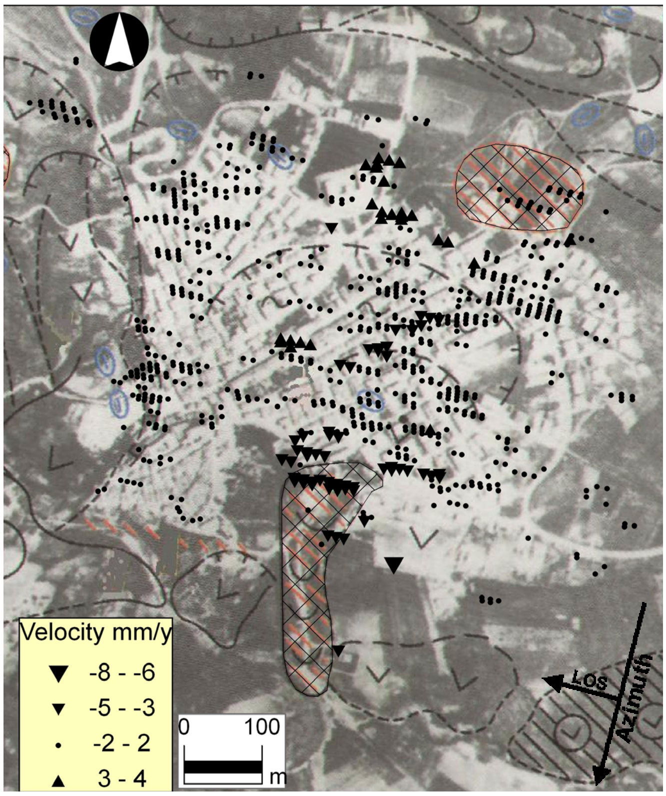

Figure 4. LOS velocity of radar targets (black symbols) in the Pietramontecorvino area. Background image is a 1976 airphoto showing photo-interpreted (after Zezza *et al.*, 1994) landslide features including: old scarps (semicircular barbed lines, dashed if uncertain), quiescent, mappable movements (with Vs and Us standing, respectively, for slides and flows) and active and quiescent landslide zones (respectively cross-hatched and hatched areas).

4.3 *Interpretation of the PS results: the case of Pietramontecorvino*

The PS pattern in the Pietramontecorvino area is much different from that of Casalnuovo Monterotaro. Several zones in the town centre and at its northern and southern outskirts include clusters of moving radar targets (Fig. 3). Indeed, Pietra Montecorvino is not a hilltop town, because it develops mostly on a SSE facing slope mantled by large landslides. However, Fig. 3 does not reveal any obvious link between the distribution of moving PS and the landslides. As in the case of the landslides, both moving and stable PS are present also in the slope areas occupied by the Flysch Rosso Formation of pre-Pliocene age (Fig. 3). This clay-rich unit, also referred to as Varicoloured Clays (Zezza *et al.* (1994), is known for its high suceptibility to landsliding.

Pietramontecorvino landslide legacy has been examined on a detailed scale by Zezza *et al.* (1994), who identified and mapped very old and more recent landslide scarps, quiescent, mappable movements, as well as active and quiescent landslide zones (Fig. 4). However, it is apparent that the pattern of moving and motionless PS bears no specific relation with the distribution of pre-existing landslides. One possible exception can be identified at the southern periphery of the town, where a significant number of slowly moving PS falls within and near the limits of a N-S elongated landslide zone (Fig. 4), interpreted as active by Zezza *et al.* (1994). Our field inspections showed that the recent landslide activity in this area is conditioned by the erosion activity of a local torrent at the slope base.

However, again, the PS one-dimensional LOS motion data alone are insufficient to resolve the nature of the observed displacements, i.e. whether they represent predominantly vertical or downslope movements or a combination of both. The fissures observed on some buildings confirm the persistence of the conditions of ground and/or structure instability, but the surface expression of the past landslide events has been substantially altered by recent town development and man activity. Clearly, in situ investigations would be needed to distinguish between the possible causes of the PS movements (e.g. local ground settlements versus true slope movements or structure instability).

In some instances, however, even a simple site inspection can allow for a straightforward interpretation of PS data. This is the case of a single moving PS situated near the SW corner of the town's football field (Fig. 5). Its position coincides with a small rotational slide: we inspected the site only after obtaining the PS results and found a semi-circular scarp with minor settlement of the field ground, as well as a locally rotated gabion (Fig. 6).

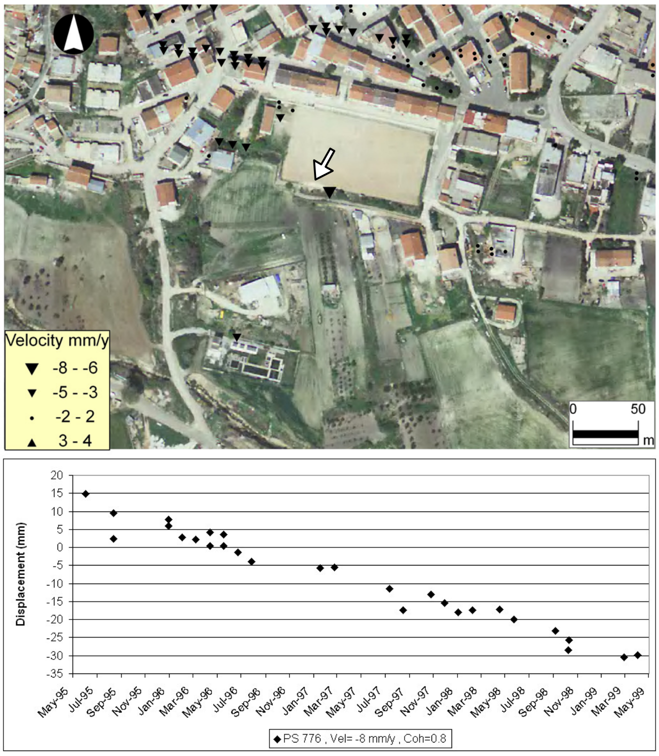

Figure 5. Top: close-up on the southern portion of the town centre with local distribution and average LOS velocity of radar targets (black symbols), superimposed on a recent ortophoto of Pietramontecorvino. White arrow points to a small landslide. Bottom: displacement time series of the PS located near the slide.

The field is also guarded by metallic wire-frame sustained by iron poles: these objects could be associated with the PS behaviour and they were locally deformed by the slide. Although the time of the initial failure is not known, the PS displacement time series (Fig. 5) indicate that the movements were taking place in the period covered by radar imagery (1995-1999). Interestingly, this is the fastest (−8 mm/y) moving radar target in Pietramontecorvino. It seems that in this case PSI allowed us to capture the slow post-failure rotation of the slide head, and that the PS motion reflects predominantly sub-vertical displacements.

Nevertheless, interpretations based on a single PS should generally be viewed as a limit case. Clearly, clusters of moving radar targets are needed for a reliable detection of ground instability.

5 DISCUSSION AND CONCLUSIONS

The PSI results indicate that the majority of PS in Casalnuovo Monterotaro are stable; these PS are concentrated within the historical centre of the town. Very slowly moving radar targets are present in two clusters situated at the eastern border of the town. This is in agreement with the observation that displacements related to landslide events or simply to ground instability occur mainly in the

Figure 6. Small rotational slide at the SW corner of Pietramontecorvino football field, whose movements were detected by PS interferometry (cf. Fig. 5). Note semi-circular scarp with minor ground settlement.

peripheries of the Daunia hilltop towns, where the urban expansion is more recent and the man-made structures acting as PS are located close to the potentially unstable slopes (Bovenga *et al.*, 2006).

In the case of Pietramontecorvino the deformations detected by PSI are present not only at the town's peripheries, but also in the centre. Indeed, this town is known for the presence of instability problems affecting many buildings. Although a major part of Pietramontecorvino appears to be sited over a large, very old landslide, we consider unlikely that the slowly moving PS (3-5 mm/y) reflect its activity. Instead, it is suggested that processes such as settlements of engineering structures, volumetric changes and post-failure creep of the clay-rich Pietramontecorvino soils and colluvia, could be responsible for the localised deformations detected by PSI. Nevertheless, a link seems to exist between the moving radar targets and recent landslide activity in the southern periphery of the town (Fig. 5).

Even though in several cases the PS displacement fields show clear evidence of moving objects in urban and peri-urban areas, local knowledge of the investigated area and site inspections are required to interpret the significance of PS motion data and to identify the mechanism of the detected deformations. In general, on slopes, surface displacements over time might be found to be in a downslope direction but such deformations might not necessarily always reflect shear movements or movements leading to shear failure, i.e. to landsliding. With the exception of "natural" PS (e.g. corresponding to rock outcrop targets), without an appropriate in situ investigation, several different interpretations of the very slow PS displacements are possible. Our PS results showing ground surface deformation changes over time on landslide susceptible slopes are very promising. However, the geotechnical parameters and geological boundary uncertainties which control PS displacements need to be investigated and better understood before they can be used directly for landslide hazard/risk zonation or for predicting (warning) of potential instabilities.

ACKNOWLEDGEMENTS

This work was supported in part by the European Community (Contract No. EVGI 2001-00055 - Project LEWIS). Images were provided by ESA under the CAT-1 project 2653.

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