A NEW APPROACH TO THE USE OF DINSAR DATA TO STUDY SLOW-MOVING LANDSLIDES OVER LARGE AREAS

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ABSTRACT

Slow-moving landslide studies over large areas call for multidisciplinary analyses supported by accurate ground displacement measurements. At present, conventional techniques can be valuably complemented by innovative satellite techniques, such as Differential SAR Interferometry (DInSAR), furnishing huge amounts of data at comparatively affordable costs. This work investigates the DInSAR data potential in landslide studies starting from the awareness of the present constraints of the technique. To this end, with reference to a sample area, located in central-southern Italy, for which detailed base and thematic maps are available, an original tool for “a priori DInSAR landslide visibility zoning” is proposed to address the choice of the most suitable image datasets. Subsequently, referring to the visible zones, the perspective of using DInSAR data for checking/updating landslide inventory maps at 1:25,000 scale is shown.

1. INTRODUCTION

The mitigation of landslide risk is a topic of great interest and several research activities have been developed in the last decades, focusing on landslide characterization, forecast and prevention, and on the evaluation and management of their consequences. With reference to the improvement of the methods for the mitigation of landslide risk, the contribution deriving from remote sensing techniques can be helpful in the detection of the area and the state of activity of landslides, the spatial analysis of their kinematical characteristics and eventually the forecast of the time to failure. In particular, the contribution of the integrated use of remote sensing techniques such as Differential SAR Interferometry has been already dealt with in the scientific literature via a number of case studies (Frunzetti et al., 1996; Squarzoni et al., 2003; Colesanti and Wasowski, 2004; Hilley et al., 2004; Strozzi et al., 2005; Crotecchia, 2006; Farina et al., 2006; Wasowski et al., 2008). However, standardized procedures for the interpretation and the confident use of DInSAR data have not been fully investigated and validated, although algorithms for image processing have become more and more sophisticated. This work introduces an innovative procedure for the a priori selection of the most appropriate image dataset for a given landslide affected area, taking into account both the acquisition geometry of the sensors and the current land-use of the area to investigate. To this aim, ERS image dataset was processed inside a well documented area, of around 489 m² within the National Basin Authority of “Liri-Garigliano and Volturino” Rivers (central-southern Italy). Once mapped the visible areas the application of low-resolution DInSAR data to landslide analysis at 1:25,000 scale over areas of unprecedented extension is shown. Then, current analyses at full-resolution, also thanks to the integration of the ERS dataset with ENVISAT images (acquired within cat-1 Project n.5618), point out perspectives of enhanced use of DInSAR data at larger scales (i.e. 1:5,000).

2. DINSAR ALGORITHMS AND THEIR APPLICATION TO LANDSLIDES.

Since the first description of the technique (Gabriel et al., 1989) several procedures have been developed: Permanent Scatterers (PS) technique (Ferretti et al., 2000; 2001), Small Baseline Subset (SBAS) technique (Berardino et al., 2002), the Coherent Point Target Analysis (CPTA) (Mora et al., 2003), the Interferometric Point Target Analysis (IPTA) (Werner et. al., 2003), the Spatio-Temporal Unwrapping Network (STUN) (Kampes, 2006), the Enhanced Spatial Differences (ESD) (Fornaro et al., 2009a), etc. The radar analysis carried out in this work is based on a two step approach. In particular, the low-resolution analysis is performed via the Enhanced Spatial Differences (ESD) approach (Fornaro et al., 2009a), which represents an upgrading of the original SBAS algorithm (Berardino et al., 2002). Differently from SBAS algorithm, which performs the phase unwrapping on each interferogram independently of the others, the ESD algorithm carries out a preliminary estimation of the mean deformation velocity and residual topography.
via modelling of the spatial phase differences of the whole interferogram stack.

Once the residual topography, temporal deformation and APD variations at small scale have been separated, the full-resolution analysis is carried out. In particular, in this work the tomographic analysis (Fornaro et al., 2009b) has been implemented in a simplified version just to locate the dominant scatterers.

The application of multipass DInSAR data to landslide studies still presents some constraints which have been widely discussed in the scientific literature (i.e. Colesanti and Wasowski, 2006).

1) Displacement data represent the one dimensional projection in the Line Of Sight (1D LOS projection) of a deformation that can actually occur in all three dimensions (Rocca, 2003).

2) The ambiguity of phase measurements implies the impossibility to track correctly (i.e., unambiguously) a the relative LOS displacement between two scatterers exceeding $\lambda/4$ (=1.4 cm for ERS) within one revisiting time interval (35 days for ERS), i.e. approximately 14.5 cm/yr. In practice it is extremely difficult to detect LOS displacement rates exceeding $8 \div 10$ cm/yr in the presence of low density of stable scatterers, such as in the case of landslides where topography and vegetation introduce a limitation in the number of detected scatterers. This limits the use of DInSAR data only to landslides ranging from extremely to very slow phenomena according to the velocity classification of Cruden and Varnes (1996).

3) Limited versatility in terms of (a.) positioning of the measurement points and (b.) revisiting time. Both factors (a.) and (b.) cannot be optimised as degrees of freedom while planning an analysis.

4) Finally, it is still difficult to forecast the coherent pixel density in rural areas without carrying out at least several processing steps on a significant number (15–20) of SAR images.

In the present study thirty-three ERS-1, ERS2 images (track 308 - frame 2765), acquired over descending orbits (years 1995 – 2000) and thirty-three ENVISAT images (years 2002 – 2008) have been processed. With reference to a test area, briefly described in the following section, the present work addresses the second and the fourth mentioned constraints focusing on landslide typologies exhibiting velocities lower than 1.6m/year (Cruden and Varnes, 1996) and the availability of DInSAR data on landslide-affected slopes which are far from being highly urbanised.

3. THE TEST AREA

The test area belongs to the northern portion of the territory of the National Basin Authority of Liri-Garigliano and Volturro rivers (NBA LGV) in central-southern Italy (Fig. 1). The choice of this territory was driven by the availability of both base and thematic maps furnished by the NBA LGV at 1:25,000 scale. These maps were produced in 2001 as results of the activities of the PSAI (Piano Stralcio per l’Assetto Idrogeologico) project, carried out by a group of experts and technicians working for NBA LGV in accordance with the Act of Italian Parliament (L. 365/2000), aimed to develop emergency plans at national scale (Cascini, 2008).

The selected area has an extension of around 489 km$^2$ and includes eleven municipalities, belonging to two Regions (Lazio and Abruzzo).

The geological map of the sample area highlights that the bedrock mainly consists of Upper Miocene arenaceous units mantled by Quaternary Age superficial deposits, characterized by talus and alluvial fans. Landslide phenomena are widespread all over the territory as it can be noticed in the available landslide inventory map at 1:25,000 scale, derived from aerial photographs and surface surveys. This map furnishes detailed information for each mapped phenomena with reference to location, typology, state of activity, extension and perimeter, as well as the assumed intensity (Cascini et al., 2005).

According to Cruden and Varnes (1996), on the basis of geomorphological criteria, three different states of activity are distinguished for the landslides within the study area, defined as: “active” (including active, reactivated and suspended), “dormant” and “inactive” (relict) phenomena.

Owing to the phase ambiguity limitation of DInSAR data processing the analysis focuses on slow-moving phenomena (Cascini et al., 2009): 204 rotational slides, 238 earth flows, 78 rotational slides-earth flows, 336 creeps, 33 earth flows-creeps, 8 deep-seated gravitational movements (according to Varnes’ (1978) classification system).

These phenomena exhibiting a significant predominance of dormant phenomena (428) on active ones (92) cover around 5% of the study area.
A FRAMEWORK FOR SLOW-MOVING LANDSLIDE APPLICATIONS

The use of low-resolution DInSAR data to study the selected landslide typologies followed the framework sketched in Fig. 2. Particularly, low-resolution DInSAR data can be used for analyses at 1:25,000 scale, which best suit the dimension of coherent DInSAR pixels on the ground (approximately 80 x 80 m). Then, in agreement with both sensor acquisition geometry and different land-uses, an “a priori DInSAR landslide visibility map” is generated. Finally, focusing on the processed DInSAR dataset a test is carried out in order to verify if remote sensed data can be used for checking/updating of landslide inventory maps.

4.1. The a priori DInSAR landslide visibility map

The choice of the proper SAR image dataset over a given area is usually performed in blind conditions although it should take into account the expected visibility of the phenomena on the slopes. In fact, the visibility of a certain portion of a slope depends on several factors such as slope aspect and inclination, vegetation cover, presence of buildings/infrastructures. Consequently, forecasting the DInSAR coherent pixel distribution still remains a difficult task to be achieved. The role played by the aspect angle and the slope inclination has been already discussed in some works (i.e. Colesanti & Wasowski, 2006). Indeed, having the available sensors a quasi polar orbits, any deformation occurring along the north–south direction originates a very small LOS projection.

To this aim, main purpose of the “a priori DInSAR landslide visibility map” is providing DInSAR data-users with a tool able to distinguish DInSAR visible areas, thus addressing the image selection dataset process.

The test was carried out at 1:25,000 scale and the input data consisted of the following available maps:
- landslide inventory map;
- aspect map;
- slope angle map;
- land-use map;
- urbanised area map.

Referring to data acquired on descending orbits and by intersecting the landslide inventory map with both the aspect map and the slope angle map (Fig. 3 a-b and Fig. 4 a-b), it was assumed that:
- areas facing west, northwest and southwest and exhibiting slope angles lower than 67° should be considered as visible;
- areas facing north and south should be considered as visible with difficulties with regard to the quantitative interpretation of the measured displacement;
- areas facing east, northeast and southeast should be conservatively considered as not visible.

However, these assumptions could result in an overestimation of the effective visible areas facing west, northwest and southwest since some areas, although having slope inclinations lower than 67°, could be in shadow due to the presence of nearby peaks. On the other hand, this can be compensated by the presence of some coherent DInSAR pixels in those areas facing east, northeast and southeast conservatively assumed as not visible in the map.

The last step required the joint exploitation of the land-use map, properly homogenised as explained in Cascini et al., 2009, and the urbanised area map. Particularly, 17 land-use categories reported in the map of NBA LGV were first homogenized into three main classes, distinguished on the basis of their characteristic of keeping constant their scattering properties in time. Class I mainly consists of urbanized areas and bare rocks; Class II includes cultivated areas and bare soils; Class III includes vegetated areas and inland waters. This last class is expected to be the worst in terms of DInSAR pixel coherence.

Class III areas were firstly intersected with urbanised areas in order to strengthen the information on the absence of built up areas. Subsequently, vegetated areas were removed from those portions previously classified as visible only according to geometric considerations.
Finally, the so-called “a priori DInSAR landslide visibility maps” were generated (Fig. 5 a-b). These maps enable to check if the area of each landslide is visible whether descending (Fig. 5a) or ascending (Fig. 5b) orbit data are available. In this regard, it is worth stressing that, depending on both the extension of a given phenomenon and the scale of the used base map, the visibility could vary within different portions of the same landslide.

The “a priori DInSAR landslide visibility map” in Fig. 5a was then validated via the processed low-resolution DInSAR data deriving from the available descending orbit image dataset. The outcomes of this comparison highlights that: 67% out of a total of 215 low-resolution DInSAR coherent pixels intersecting landslide affected areas concentrate on visible areas; 19% lay on areas visible with difficulties and only 14% can be found in areas assumed as not visible. Moreover, the density within the visible areas (11.5 low-resolution DInSAR pixels per km²) is far higher than within not visible areas (3.3 low-resolution DInSAR pixels per km²).

4.2. Low-resolution DInSAR data towards the checking/updating of landslide inventory maps

Once the selected SAR image dataset has been processed, the DInSAR coherent pixel coverage
achieved on landslides turns out to be relevant to remote sensed data analysis. To this end, referring to the sample area, the low-resolution ESD DInSAR coherent pixel map was overlaid on the landslide inventory map (1:25,000 scale) and one single mapped phenomenon was assumed to be “covered” if at least one low-resolution DInSAR coherent pixel was found on it. Although DInSAR data were processed only on descending orbit, 301 slow-moving landslide phenomena (belonging to the typologies indicated in section 3) resulted covered by low-resolution DInSAR data. This corresponds to an average percentage of around 34% out of the total of 897 landslides and creeping phenomena mapped within the territory of the 11 investigated municipalities.

As discussed in section 2 the limited coverage on landslide affected slopes is one of the main constraints to the applicability of DInSAR data to landslide study. Anyway, when dealing with analyses over large areas, where sufficient ground truths may be lacking, the availability of diffused information on ground displacements, recorded either within or outside mapped phenomena, can be useful to carry out several analyses. One of these analyses can pursue the checking/updating of landslide inventory maps with reference to both the state of activity of mapped phenomena and the detection of evidence of movements in landslide-prone areas.

To this end, DInSAR mean velocity values, derived from displacement time series computed along the LOS direction, were firstly tested as ground surface movement indicators for the observation period at hand (Cascini et al., 2008). Particularly, it was assumed a displacement rate threshold of 1.5 mm/year for conditions of movement (values higher than 1.5 mm/year) or no-movement (values lower than 1.5 mm/year). This threshold, based on experimental evidences, was selected as a conservative rate of the average deformation (Colesanti et al. 2003).

The setting of the abovementioned threshold allowed the detection of displacements within each SAR covered landslide whose activity state is defined in the landslide inventory map on the basis of geomorphological criteria. This analysis was carried out with reference to rotational slides, earth flows and rotational slides-earth flows whose total amount in the study area is 520; 169 (around 32%) of those resulted covered by DInSAR data.

The results show that almost 84% of the DInSAR covered dormant landslides (144) exhibit evidence of no-movement. On the other hand, the percentage of active landslides (25) with moving coherent DInSAR pixels is about 24%, on the average (Cascini et al., 2008). The cross-check of low-resolution DInSAR data and the Landslide Inventory Map was then extended to the analysis of moving/not moving coherent pixels on those portions of the territory mapped as hollows on the geomorphological map (1:25,000 scale) of the NBA LGV (Fig. 15). These zones are characterized by geomorphological settings quite similar to landslide affected areas, also exhibiting the same landslide predisposing factors. Particularly, with reference to the whole study area 1261 hollows were identified. The low-resolution DInSAR moving/not moving coherent pixel map was firstly extended out of the mapped landslide affected areas and then overlaid on the geomorphological map, thus allowing the detection of 63 hollows where a clear evidence of movement was recorded.

Figure 6. An example of low-resolution moving DInSAR coherent pixel detection within portions of the territory mapped as hollows. (1) Hollow with moving DInSAR coherent pixel; (2) hollow not covered or with not-moving DInSAR coherent pixel; (3) dormant rotational slide; (4) active rotational slide; (5) dormant earth flow; (6) active earth flow; (7) dormant rotational slide - earth flow; (8) active rotational slide - earth flow; (9) creep phenomenon (after Cascini et al., 2009).

5. CONCLUSIONS AND PERSPECTIVES

The checking/updating of landslide inventory maps may call for expensive and time consuming analyses and surveys especially when dealing with large areas. To this end, a contribution can be furnished by DInSAR data whose use will not be straightforward until standardized procedures concerning the landslide analysis over large areas are not properly developed and validated.

Accordingly, starting from current limits of the techniques, the presented work firstly introduced evaluations on the sensor acquisition geometry, topographic data and land-use classes to generate an original “a priori DInSAR landslide visibility map” of landslide affected areas. Owing to the discussed constraints in slope monitoring (section 2.3), this map can provide data-users with valuable information on the
expected visibility of the portion of the territory to study, thus enabling to save both money and time for image processing. Once the visible areas have been individuated, low-resolution DInSAR data provided useful elements for activities concerning checking/updating of landslide inventory maps either within or outside areas mapped as landslide phenomena. Further interesting aspects could be deepened via the analysis of full-resolution DInSAR data. In this regard, an example of the ongoing analysis on ENVISAT dataset processed via Differential tomography algorithm is shown in Fig. 7.

![Figure 7. Full-resolution DInSAR coherent pixels distribution, for a portion of the municipality of Frosinone (Italy).](image)

The main characteristic is the higher DInSAR data density with pixels concentrating on buildings and roads. This aspect sounds really appealing in landslide studies since even isolated structures located on landslides could be detected when conditions of visibility are granted. The detected man-made works, in turn, could act as ground benchmarks providing the researchers with useful information on the local kinematics of the phenomenon to study. With this regard the characterization of a given landslide with the help of DInSAR data mainly depends on the scale of the analysis, the extension and the complexity of the phenomenon. For instance, at least one DInSAR coherent pixel on the main landslide portions (e.g. head, main body, accumulation zone) could be enough for analysis at 1:25,000 scale; whereas this could be not enough to highlight different kinematical behaviour within the same phenomenon at larger scales (i.e. 1:5,000; 1:2,000). These aspects will be further deepened also thanks to the complete ENVISAT ascending/descending dataset which will certainly enhance the process of validation and interpretation of DInSAR data in this kind of problems at the scale of the single phenomenon. In conclusion, notwithstanding the limited visibility within areas covered by DInSAR data the proper use of these techniques hold the premise for furnishing valuable contributions to landslide zoning at different scales. To this end, the launch of new sensors with enhanced resolution and reduced revisiting time will provide much more information thus allowing further validation of the technique.

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REFERENCES


Rocca, F. 2003. 3D Motion recovery with multi-angle and/or left right Interferometry. Proc. 3rd International Workshop on ERS SAR Interferometry (FRINGE 2003), Frascati (Italy), 2–5 December 2003. ESA SP-550, available also online: http://earth.esa.int/fringe03/proceedings/posters/62_r.pdf (accessed July 13, 2009)


