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Advanced low- and full-resolution DInSAR map generation for slow-moving landslide analysis at different scales

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A B S T R A C T

A proper analysis of slow-moving landslides calls for several efforts aiming at their characterization and mapping. Considering the uncertainties related to the landslide inventory maps the integration of conventional techniques with remote sensing data, such as differential SAR interferometry (DInSAR), can furnish a valuable contribution in a number of case studies. However, standardized procedures for the interpretation and the confident use of DInSAR data, according to landslide zoning developments, have not been fully investigated and validated, although algorithms for image processing have become more and more sophisticated. This work addresses a new methodology for the use of DInSAR data, at both full- and low-resolutions, in landslide analyses at different scales via the integration of remote sensing data with simple geomorphological models and geometric considerations. The methodology is tested inside a well documented area in Central–Southern Italy where an advanced dataset on base and thematic maps is available.

1. Introduction

Displacement data can be profitably used to characterize both the boundaries and the state of activity of slow-moving landslide phenomena. To this aim, the measurements need to be efficient in terms of time and budget especially when dealing with analyses over large areas. In this regard, the use of advanced satellite techniques, which involve data achieved by Synthetic Aperture Radar (SAR) (Gabriel et al., 1989), can turn out to be extremely useful. In particular, the differential SAR interferometry (DInSAR) can complement with traditional topographic techniques to obtain a comparable accuracy of ground surface displacements while being less expensive and time consuming. However, the application of DInSAR techniques to landslide phenomena is a relatively new and still challenging topic and only few successful case studies are discussed in the scientific literature (Fruneau et al., 1996; Squarzoni et al., 2003; Berardino et al., 2003; Colesanti and Wasowski, 2004; Hilley et al., 2004; Strozzi et al., 2005; Cotecchia, 2006; Farina et al., 2006; Wasowski et al., 2008).

This paper is aimed to overcome some of the present difficulties by introducing a new methodology for DInSAR data interpretation in areas for which a proper geomorphological and topographic knowledge is available.

The methodology is essentially based on the integration of information concerning landslide features and related ground displacements. The first step is the generation of the a priori DInSAR landslide visibility map (Cascini et al., 2009). Then, DInSAR data interpretation is based on the joint use of remote sensed data and simplified geomorphological models. The procedure is tested at both medium (i.e. 1:25,000 scale according to Fell et al., 2008) and large scales (i.e. 1:5000 scale, Fell et al., 2008) within a sample area extending for around 489 km^2 in the territory of National Basin Authority of Liri–Garigliano and Volturno (NBA-LGV) rivers (Central–Southern Italy), where 897 slow-moving landslide phenomena were accurately mapped (see Section 3).

2. Multipass DInSAR techniques and current limits to their application to landslide analysis

Since the first description of the technique (Gabriel et al., 1989), most of the DInSAR applications were based on single interferograms (i.e. using an image pair) or few interferograms. The advantage of these simple configurations is the flexibility to provide (qualitative) information on deformations, even with a reduced SAR data availability. However, standard two pass DInSAR is limited by the presence of at least two error sources: the APD (Atmospheric Phase Delay) variation and the inaccuracies of the external Digital Elevation Model (DEM) involved in the cancellation of the topography component from the signal interferences.

The above limitations were overcame for the first time by Ferretti et al. (2000, 2001) via the persistent scatterers (PS) technique that exploits long acquisition sequences, characterized by view and temporal diversity.

At present two classes of techniques are available for the analysis of phase signals in interferometric stacks: persistent scatterers

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interferometry (PSI) (e.g. Werner et al., 2003; Kampes, 2006) and small baseline approaches (e.g. Berardino et al., 2002; Mora et al., 2003).

In the first class, the analysis is carried out at full resolution on stable scatterers in order to separate the atmospheric, topographic and deformation components. Key assumption is the stability of the radar response, which occur mainly in the presence of dominant point scatterers.

In the case of small baseline techniques, the scattering is supposed to be distributed within the resolution cell and spatial multilooking is implemented to enhance the phase stability. As a consequence of this operation, the spatial resolution is degraded with respect to the PSI approach.

In this sense, small baseline approaches are more suitable for analysis over wide areas. Nevertheless, a product of the small scale analysis is the estimate of the Atmospheric Phase Delay (APD), which allows the implementation of a subsequent large scale analysis carried out at full resolution.

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. The model assumes the phase to be linearly related to the mean deformation velocity and residual topography via the temporal and spatial baselines, respectively. During this step the selection of the sparse grid of coherent pixels is refined according to the degree of fitting of the signal to the model.

Once the residual topography, temporal deformation and APD variations at small scale have been separated, the full-resolution analysis is carried out. In particular, the tomographic analysis (Fornaro et al., 2009b) has been implemented. This technique has been proven to constitute an extension of the PSI techniques: by using the amplitude and the phase of the received signal, it allows achieving a higher robustness degree in the detection of persistent scatterers, but also it allows the separation of possible scatterers interfering in the same resolution cell. Interference of target in the same pixel generally occurs in the analysis of urban areas due to the steep topography: for the application under investigation we did not apply such a super-resolution analysis but, based on the higher degree of detection robustness, we only located, as usually done for PSI, the dominant scatterer.

As for the application of multipass DInSAR data to landslide studies, the scientific literature (i.e. Colesanti and Wasowski, 2006) has widely discussed the current limits:

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; Manzo et al., 2006).
2) The ambiguity of phase measurements implies the impossibility to track correctly (i.e., unambiguously) 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 8–10 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 work thirty-three images (track 308–frame 2765), acquired over descending orbits of the European Remote Sensing (ERS-1, ERS2) satellite systems, spanning the time interval from March 1995 until February 2000, have been processed. The proposed procedure is aimed to tackle the limit related to point 1, correctly address point 2 and reduce the uncertainties related to point 4.

3. The test area

DInSAR data cover a test area belonging to the northern portion of 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 project (Piano Stralcio per l'Assetto Idrogeologico), 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 zone the landslide risk all over the Italian territory (Cascini, 2008).

The test area has an extension of around 489 km^2 and includes eleven municipalities, belonging to two Regions (Lazio and Abruzzo) (Fig. 1). The geological map 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 area (covering around 5% of the whole 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 and areal extension (Cascini et al., 2005).

Owing to the phase ambiguity limitation of DInSAR data processing (point 2 in Section 2), in this work the analysis of landslides is focused on the typology of phenomena ranging from *extremely* to *very slow* velocity classes (i.e. lower than 1.6 m/year according to Cruden and Varnes, 1996). In the study area a total number of 897 slow-moving landslides are mapped (Peduto, 2008; Cascini et al., 2009); according to Varnes (1978) they are classified as: 204 rotational slides, 238 earth flows, 78 rotational slides–earth flows, 336 creeps, 33 earth flows — creeps, and 8 deep-seated gravitational movements. On the basis of geomorphological criteria, three different states of activity are distinguished for these landslides, defined as follows: "active" (including active, reactivated and suspended),

Fig. 1. The test area.