DETECTING LANDSLIDE ACTIVITY BY SAR INTERFEROMETRY

A. Refice[(1)], L. Guerriero[(1)], F. Bovenga[(1)], J. Wasowski[(2)], N. Veneziani[(3)],

S. Atzori[(4)], A. R. Ferrari[(4)], M. Marsella[(4)]

[(1)] ***Dipartimento Interateneo di Fisica, Bari (Italy)***
Via Amendola 173, 70126 Bari
E-mail: `alberto.refice@ba.infn.it`

[(2)] ***Centro di Studi sulle Risorse Idriche e la Salvaguardia del Territorio (CERIST) - CNR, Bari (Italy)***
c/o Istituto di Geologia Applicata e Geotecnica, via Orabona 4, 70125 Bari
E-mail: `wasowski@area.ba.cnr.it`

[(3)] ***Istituto Elaborazione Segnali e Immagini (IESI) - CNR, Bari (Italy)***
Via Amendola 166/5, 70126 Bari
E-mail: `veneziani@iesi.ba.cnr.it`

[(4)] ***Dipartimento di Idraulica, Trasporti e Strade (DITS), Università "La Sapienza", Roma (Italy)***
Via Eudossiana 18, 00184 Roma
E-mail: `maria.marsella@uniroma1.it`

Abstract

Operational monitoring of slope instabilities by SAR Interferometry poses a number of challenges due to the limited spatial extent of the landslide areas and rainy conditions usually associated with mass movement events. In this work we present the results of the application of both conventional DInSAR techniques, and a point-by-point, multitemporal study of the long-term stability of selected high-coherence objects on the ground.

The techniques were applied to selected test sites in the Central and Southern Apennines of Italy. Results obtained by processing a number of ERS SAR images acquired over the test areas before, during and after critical events are presented. The evaluation of the results is performed through the comparison with data from ground based techniques. The various factors influencing the suitability of the selected data for interferometric applications, i.e. resolution, temporal and spatial baselines, and times of acquisition, are assessed.

For one of the test sites, an application of the so-called "permanent scatterers" (PS) technique, originally proposed by the POLIMI group, is being attempted to monitor small displacements between points exhibiting a high long-term phase coherence and a strong and stable backscatter level.

1 INTRODUCTION

Landslides are among the most costly catastrophic events in terms of human lives and infrastructure damage. Their occurrence is connected to a large number of environmental variables and thus is difficult to foresee. The role of EO data for landslide hazard assessment has been recently reviewed by CEOS [1].

Differential SAR interferometry (DInSAR) is nowadays reaching operational levels in monitoring small earth-surface displacements such as those associated with earthquakes or volcanic activity [2, 3]. However, several problems are encountered when trying to apply the high vertical sensitivity of DInSAR to small-area phenomena such as landslides. The encouraging results of some recent studies on the subject [4, 5, 6, 7] seem to be the result of particularly favourable circumstances and environmental conditions such as the presence of large, scarcely vegetated and very slowly-deforming slopes, availability of interferometric pairs with short temporal and spatial baselines, suitable viewing direction and absence of on-site precipitation during or shortly before acquisition [8].

In this paper, we present some results obtained in the framework of the ESA-AO3-320 project, concerning the application of SAR interferometric and differential interferometric techniques to the study of two landslide sites in Southern and Central Italy. The first one is located in the Sele river valley (Campania region), which includes several intermittently

Table 1: ERS image dataset

	Ascending passes		
	Sensor	Orbit no.	Date
1	ERS-1	6014	08/09/92
2	ERS-1	6515	13/10/92
3	ERS-1	8018	26/01/93
4	ERS-1	8519	02/03/93
5	ERS-1	9020	06/04/93
6	ERS-1	9521	11/05/93
7	ERS-1	10022	15/06/93
8	ERS-1	10523	20/07/93
9	ERS-1	11024	24/08/93
10	ERS-1	11525	28/09/93
11	ERS-1	12026	02/11/93
12	ERS-1	19384	30/03/95
13	ERS-1	19885	04/05/95
14	ERS-1	20887	13/07/95
15	ERS-2	1214	14/07/95
16	ERS-1	21388	17/08/95
17	ERS-1	22390	26/10/95
18	ERS-2	2717	27/10/95
19	ERS-1	22891	30/11/95
20	ERS-1	23392	04/01/96
21	ERS-1	23893	08/02/96
22	ERS-1	24895	18/04/96
23	ERS-1	25396	23/05/96
24	ERS-2	5723	24/05/96
25	ERS-1	25897	27/06/96
26	ERS-2	6224	28/06/96

Table 2: Ground monitoring results and selected ERS dataset.

***In situ* topographic and inclinometric measurements**				**ERS data acquisitions**	
Dates	**Landslide Movement velocities (avg. over obs. Period)***			**ASC Orbit number (frame 810)**	**Acquisition dates**
	Crown area	***Main flow***	***Toe (accumulation area)***		
25.03.95	**< 1** mm/day	**40** m/month (**30** m/week between12-17 May)	**< 1** mm/day	19384 E1	30.03.95
18.05.95				19885 E1	04.05.95
23.06.95	**2-4** mm/day	**35** m/month*	**2-6** mm/day		
14.10.95	**6-9** mm/day	**25** m/month	**10-26** mm/day	20887-1214 E1/2	13-14.07.95
				21388 E1	17.08.95
23.05.96	**4-5** mm/day	Sliding slows down progressively (~**1** m/month)	**1** mm/day	22390-2717 E1/2	26-27.10.95
				22891 E1	30.11.95
				23392 E1	04.01.96
				23893 E1	08.02.96
				24895 E1	18.04.96
				25396-5723 E1/2	23/24.05.96
				25897-6224 E1/2	27/28.06.96

* Velocities represent minimum, long-term average values; maximum short-term velocities could be higher.

active landslides. We focus on the 1993 Acquara-Vadoncello landslide, near the small town of Senerchia, for which extensive ground-truth data are available from on-site engineering geology surveys [9]. The second test site is situated in the “Valle del Biferno” (Molise region), and concerns the Covatta landslide.

A large number of ERS SAR scenes were examined on both sites. DInSAR techniques were applied, both in the “conventional” form, by extracting spatially-extended differential phase fields, and through application of innovative techniques, namely the so-called “permanent scatterers” (PS) approach, proposed by the POLIMI group [10].

Conventional DInSAR shows uncertain results for the Senerchia test site, mainly due to the small spatial extension of the Acquara-Vadoncello landslide, which would probably require higher resolutions than that available from ERS SAR data. The PS approach reveals interesting features which call for further studies in this direction.

In the case of the Covatta landslide, the analysis allowed to localize and outline areas affected by slope instability. The observed movement data from DInSAR were in agreement with ground-truth data, and allowed to detect precursory terrain movements. It was also possible to observe previously undetected landslide activity over a nearby site.

THE SENERCHIA TEST SITE

2 THE DATASET

2.1 ERS images

Table 1 summarizes the dataset used for the study, consisting of 25 ERS SAR frames taken on ascending passes (frame no. 810), including 4 tandem pairs.[1] The total time span of the scenes is almost 4 years, with spatial baselines ranging from less than 2 m to about 1300 m. Fig. 1 shows the relative distribution of spatial and temporal baselines.

[1] Although the whole dataset assigned to the project included also some descending passes, they are not considered in the present work, because their acquisition geometry is unfavourable to the analysis of the test landslide site. They are being considered for use in conjunction with the ascending passes over other landslide sites, present in the same scenes described in this work.

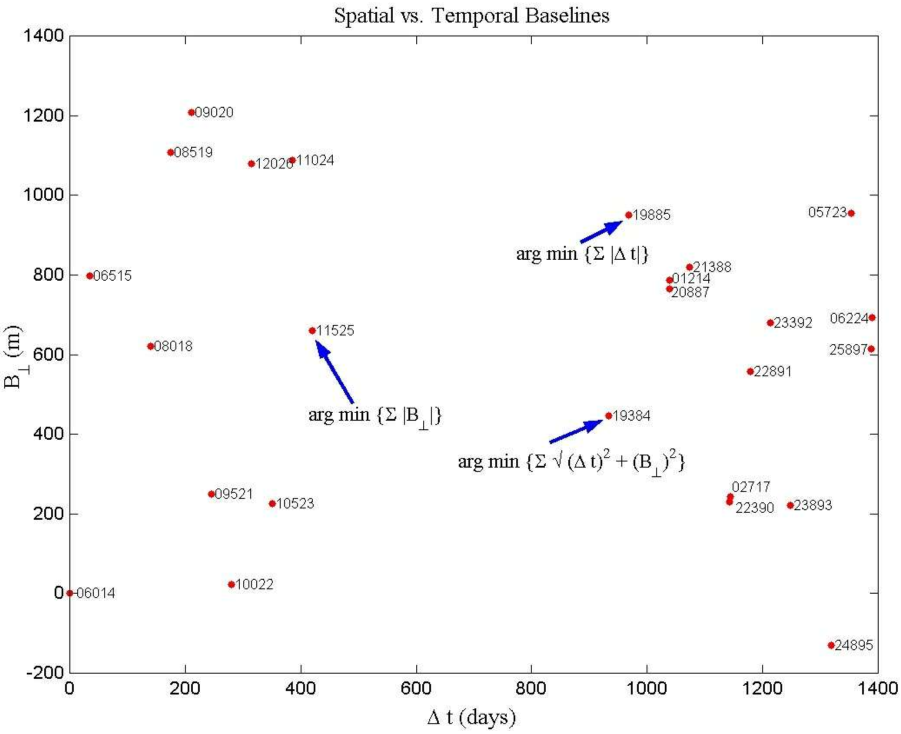


Figure 1: Spatial vs. temporal distribution of the ERS dataset. The datatakes minimizing $\sum |B_\perp|$, $\sum |\Delta t|$, and $\sum \sqrt{(B_\perp)^2 + (\Delta t)^2}$, respectively, are evidenced.

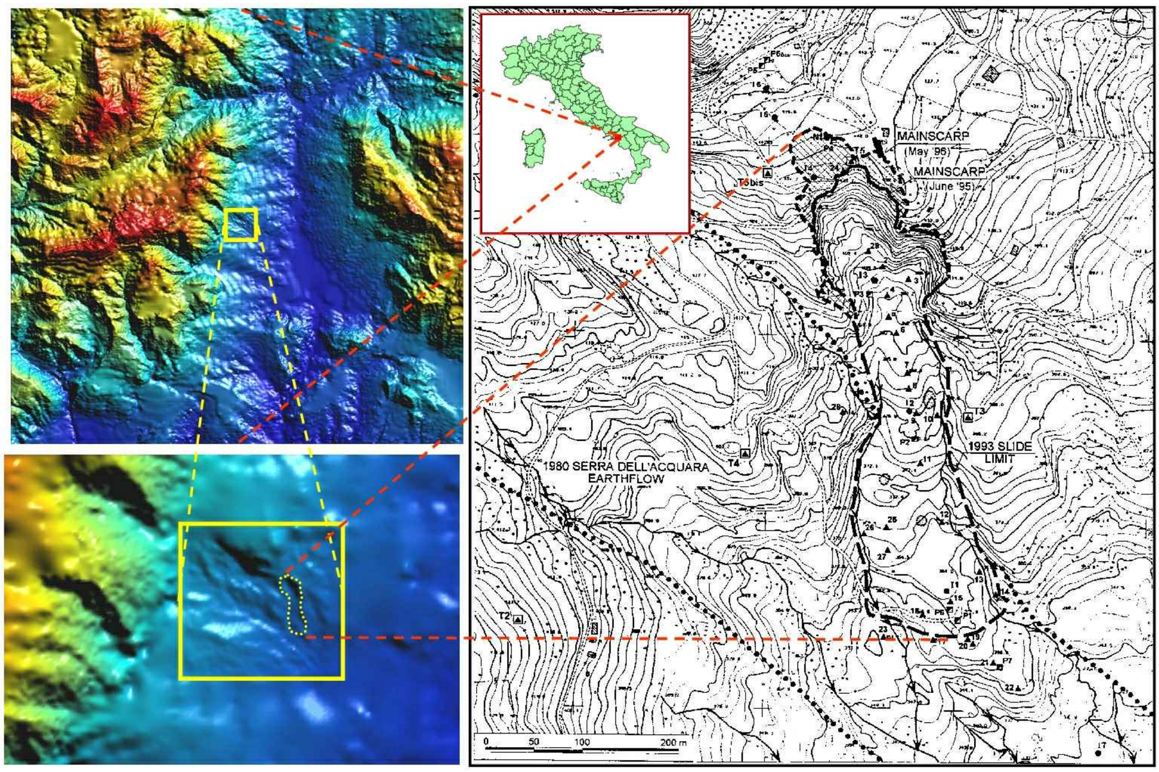


Figure 2: Location of the 1993 Acquara-Vadoncello landslide and the huge Serra dell'Acquara earthflow. The digital elevation model shown on the left is obtained by local updating of digital contour lines (see text).

2.2 Topographic data

A set of topographic digital elevation models (DEMs) was used. A coarser DEM, covering about 20×20 km^2, was obtained by digitization of 1:25000 contour maps. A more precise DEM, covering the Acquara-Vadoncello landslide area, was obtained from 1:2000 contours. A "merged" dataset was obtained by adding the latter, finer set of contour lines to the first, and re-interpolating and gridding a new DEM. This product covers an area large enough for a reliable InSAR processing and provides more precise and updated elevation data over the landslide area. The area location and a hill-shaded view of the DEM are shown in fig. 2.

2.3 Ground Truth

The *in situ* monitoring data are schematized in tab. 2, and shown together with the part of the SAR image dataset covering the period of landslide activity. The ground truth refers to a re-activation period of the landslide, which began in March, 1995. The velocities reported in the table were recorded through repeated inclinometric borehole measurements and topographic surveys [9]. They are subdivided into crown, main flow, and accumulation (toe) areas.

As can be seen, the part of the ERS dataset reported in tab. 2 temporally spans most of the period covered by ground measurements. The main flow area shows displacement rates reaching 30 m per week in the period of maximum activity. However, starting from October, 1995, the movements slowed down. The crown and toe areas, instead, show much lower movement rates for all the duration of the event. In summary, the amount of displacement spanned by some of the interferometric pairs which can be formed with the images in the dataset, especially the tandem pairs, should, according to this *a priori* analysis, fall within the limits of detectability of movement signals through DInSAR techniques.

3 DIFFERENTIAL INSAR PROCESSING

3.1 "Conventional" DInSAR

Interferometric processing was attempted for a large number of InSAR pairs with various temporal and spatial baselines. The pairs acquired at intervals of 34 to 36 days did not show sufficient coherence over the area of interest. The four tandem interferograms show acceptable coherence over part of the area covered by the DEM. However, the highest-relief mountain areas at the E and W sides of the Sele valley were affected by strong decorrelation, probably due to volumetric effects caused by vegetation (trees). Tandem pairs were thus used for 24-hour movement detection. Precise geocoding and orbit corrections were applied to the imagery in order to obtain standard georeferenced phase, amplitude and coherence maps.

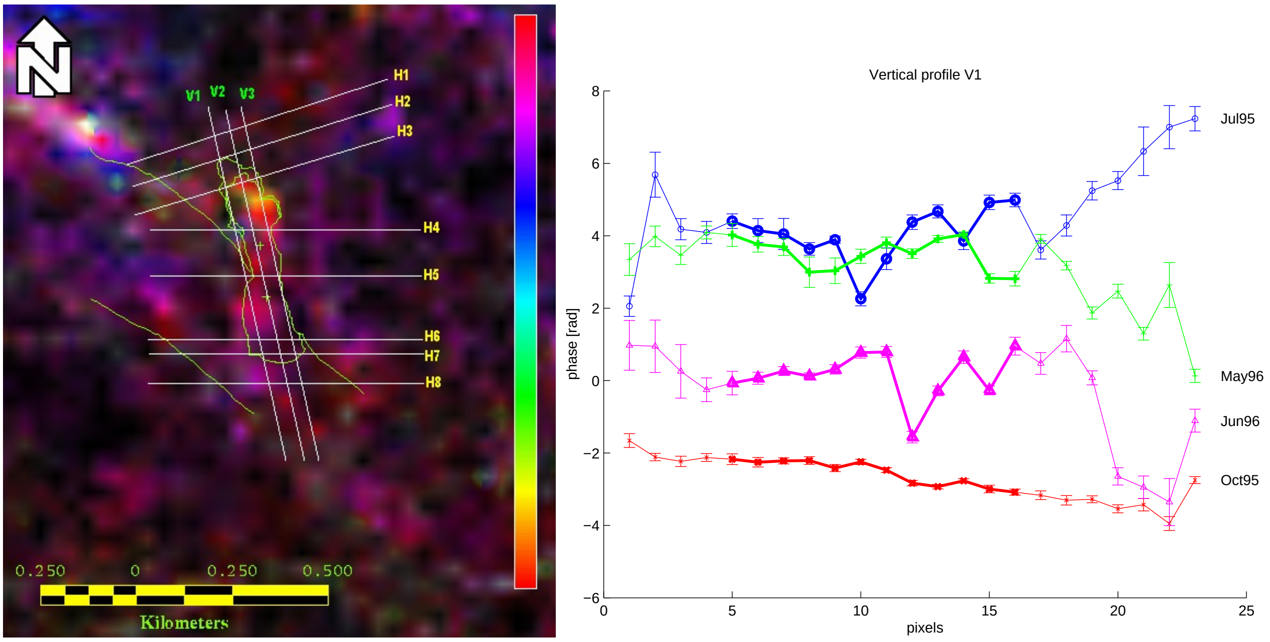
Several phase profiles were extracted over the landslide area. The map in fig. 3-(a) shows a portion of an interferogram covering the landslide area. The trends of multitemporal differential phase along a selected profile are shown in fig. 3-(b). Because of the coherence problems, a ground resolution of 40×40 m^2 was used to assure reliable phase and coherence estimates.

The profile shows phase variations which, if interpreted as differential signals, may indicate movements of up to a few cm in the landslide crown and toe areas. These movements can be inferred from the short-baseline tandem pair of July 1995, which coincides with the period of increased landslide activity (see tab. 1). The October 1995 tandem pair, corresponding to a period of much lower landslide activity, shows weaker phase variations. The other two tandem pairs also show differential phase signals, but, having longer baseline, they are more sensitive to topography and thus to DEM errors. Therefore, no clear inferences can be made with respect to the low-magnitude ground movements registered through *in situ* controls.

The example of our case-study indicates that conventional DInSAR methods have serious limitations when applied to a relatively small and complex landslide area. In order to overcome these limits, different approaches are being currently attempted, the most promising of which appears to be the study of the so-called "permanent scatterers", or PS, proposed by Ferretti *et al.* [10].

3.2 PS processing

This methodology allows to overcome most of the resolution, temporal and spatial baseline limitations hindering conventional InSAR processing, by selecting isolated points on the ground which exhibit stable interferometric phase behaviour over time. The original procedure has been applied in a number of studies on terrain instabilities, mainly over urbanized areas. We are currently attempting to apply and assess the PS approach for rural sites such as the one treated here, with low densities of infrastructures.



(a) (b)

Figure 3: (a): location of sample profiles taken over the Acquara-Vadoncello landslide area. The background image is an IHS combination of the July 1995 tandem pair. (b): multitemporal differential phase trends of a longitudinal profile (V1 in (a)). The profile portions within the landslide limits are marked by thick lines.

We basically follow the approach of [10, 11]. All 25 images were coregistered to a single master. The latter was chosen so as to minimize the maximum range of spatial and temporal baselines (priority was given to the spatial baseline minimization criterion). Referring to fig. 1, the datatake with orbit no. 11525 was chosen as common master image.

As a first product of this processing, the coregistered image stack allowed to easily obtain a sum of the amplitudes of all the single SAR images. This procedure strongly reduces speckle noise without affecting the resolution. As a result, this “incoherent sum” of images shows a great deal of details at large scale (full single-look resolution).

A preliminary estimate of the presence and location of PSs was performed by studying the stability in time of the backscatter amplitudes of strong scatterers. To this end, after an equalization procedure, the μ/σ ratio was computed for every image pixel, where μ and σ are the amplitude mean and standard deviation, respectively, computed over a single, given pixel and across the stack of all 25 images. Theoretically, high values of this ratio should indicate a high relative stability of backscatter, and this in turn should be a hint for stable phase behaviour in time.

Fig. 4 shows the positions of the points which were found to have $\mu/\sigma > \tau$, where τ is a certain threshold value, chosen by analysis of the data characteristics (see [11] for details).

As a preliminary estimate, the τ threshold was set to a quite low value, in order to avoid neglecting some possible candidates for a further study. These candidate PSs appear spatially well distributed, with increasing density over areas where many man-made features are located, such as in the valley bottom. To better understand their spatial distribution, the preliminary PS map has been projected into UTM coordinates. Fig. 5 shows the superposition of some of the detected PS on a georeferenced air photo of the same area. Although the geocoding process considerably degrades the resolution, some of the preliminary PSs can be seen to be close to sparse man-made features such as houses, road crossings, etc. Work is in progress toward a better characterization of such scatterers, mainly in terms of their phase stability in time.

The Covatta test site

4 Description of the site

This test case apparently satisfies the requirements for the applications of DInSAR technique: the landslide is about 1400 m long and about 240 m wide; the movements are compatible with the SAR sensitivity; the body of landslide is scarcely

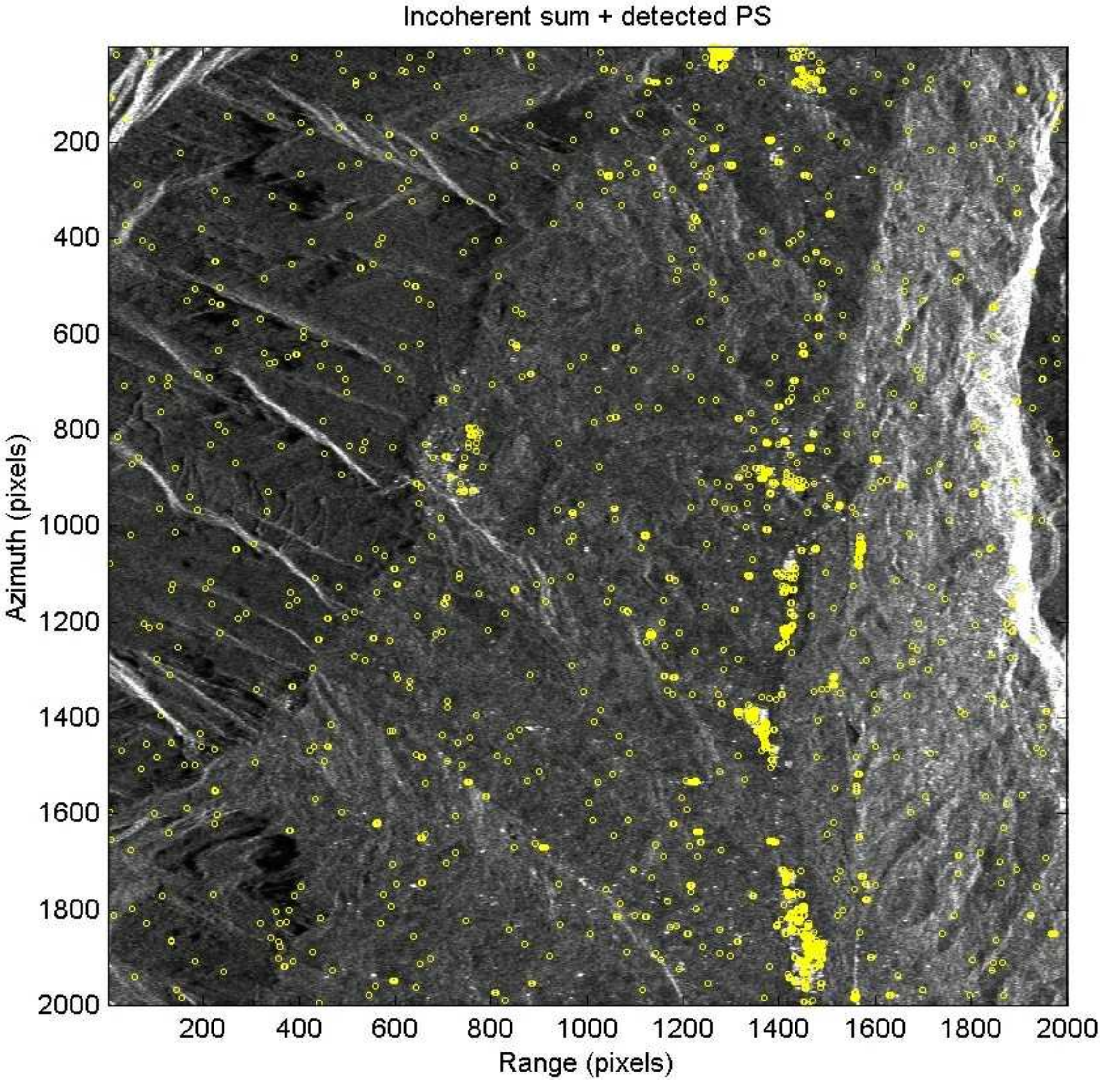


Figure 4: Incoherent sum of the 25 coregistered, interpolated images. The positions of the detected PSs are indicated by the yellow circles.

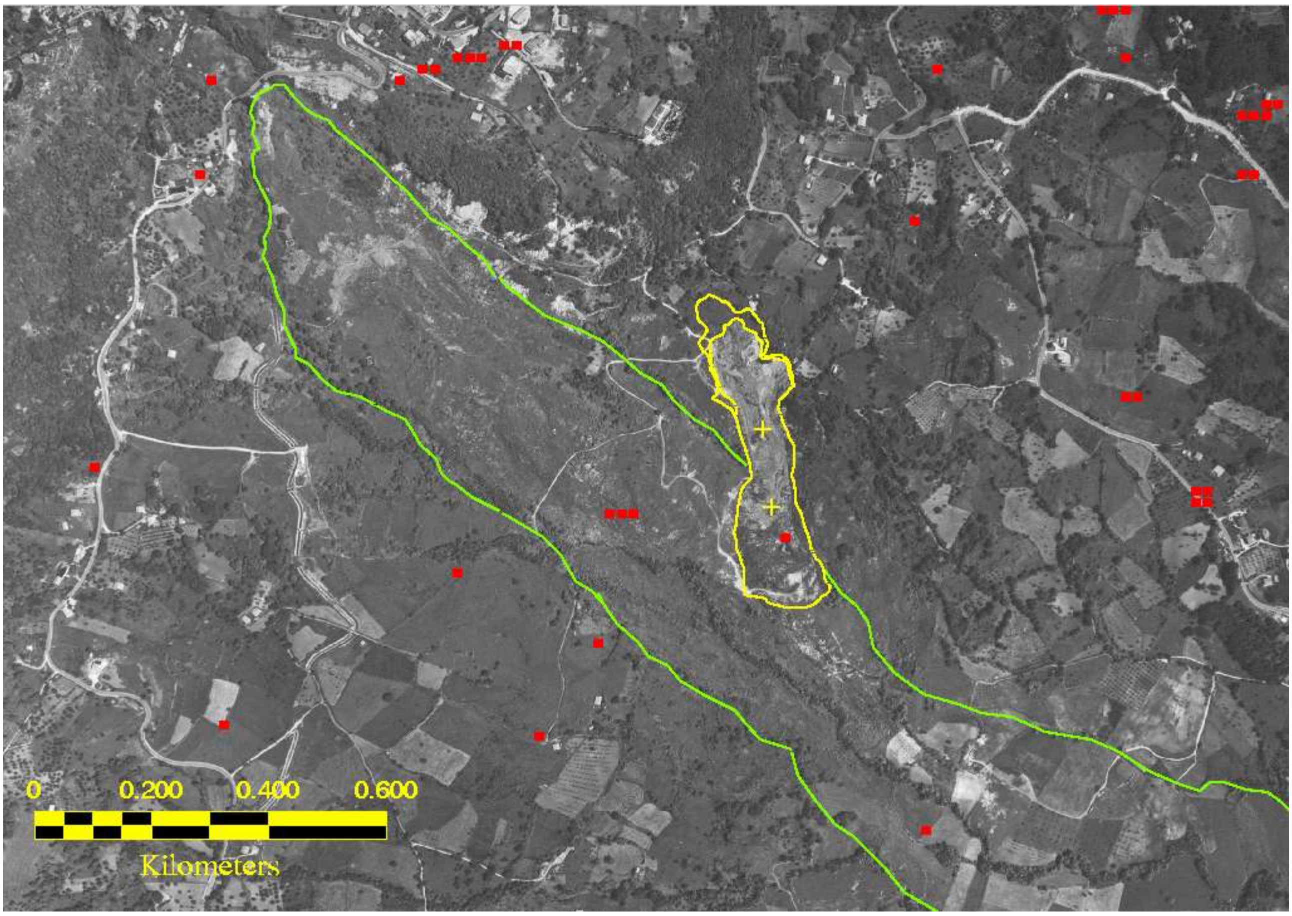


Figure 5: Superposition of the candidate PS positions on an air photo of the Senerchia test site. PS positions are represented by red dots. The Acquara-Vadoncello landslide contour is evidenced by the yellow lines, while the green line delimits the older Serra dell'Acquara earthflow (triggered by an earthquake in 1980).

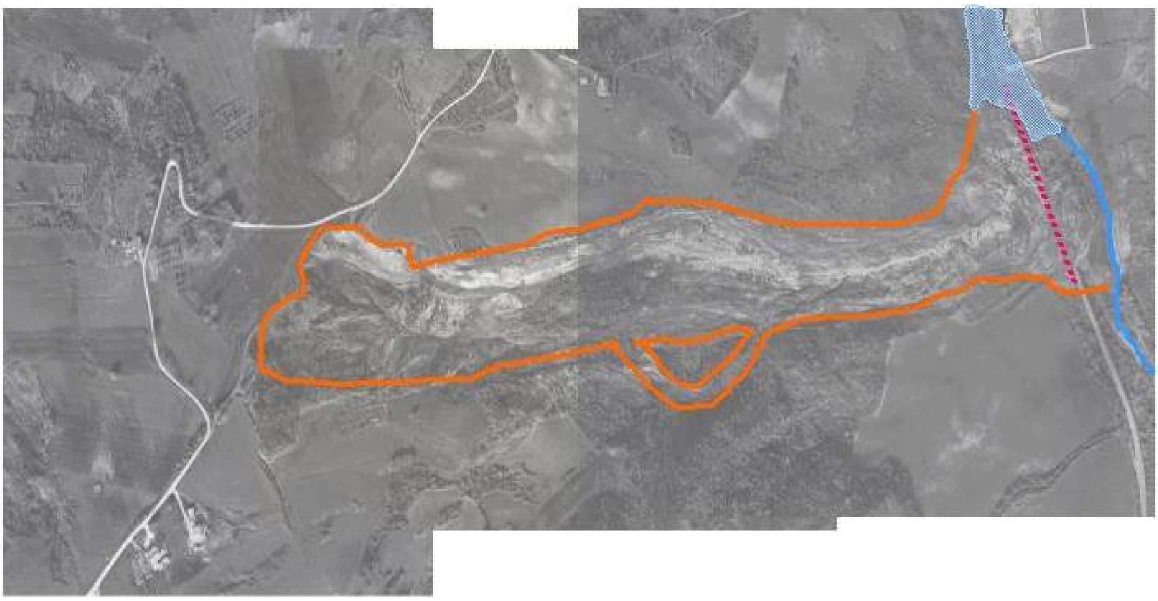


Figure 6: Aerial view of the Covatta Landslide

Table 3: Main parameters of the Covatta landslide.

Main parameters of the Covatta landslide	
Longitudinal length	~ 1 km
Mean width	240 m
Depth	10-20 m
Mean slope	12°
Mass balance	2,0 x 10^6 m^3

vegetated. Furthermore, many ancillary data are available on the same site, collected before and after the major landslide occurred. The landslide of the “Valle del Biferno”, known as the Covatta landslide [12], re-activated on the 12th of April, 1996, destroying the viaduct Pozzillo and interrupting the road S.S. 647. The river Biferno was also obstructed. This type of landslide occurs very frequently in the Italian Apennines. The landslide is an earth flow of varicolored-scaly clays. The displacements observed on the flow front reached about 100 m during the first days; afterwards the flow velocity was about 10 cm/day. Presently, the landslide is still active showing displacements of the order of a few centimeters per month. The area surrounding the landslide is covered by different types of sparse and low vegetation; no vegetation is present on the landslide. An aerial view of the landslide is shown in fig. 6. The main parameters of the landslide are listed in tab. 3.

5 THE DATASET

5.1 Image selection

The selection of images was performed by taking into account the perpendicular baseline, meteorological conditions and soil water content. Considering the N-NW slope of the landslide, the selection of the ERS images was made among descending orbits. In order to minimize the presence of atmospheric artifacts, the meteorological conditions were also controlled on NOAA images. The dataset initially requested to ESA includes 10 images, listed in tab. 4. Unfortunately, one product was affected by missing lines and one tandem pair was affected by some orbital fault. As a consequence, it

Table 4: Image list for the Covatta test site.

First dataset									
PJIDPJ	Sat	Sensor	Prod.	Orbit	Frame	Acq.Date	Acq.Time	Lat	Long
322202	E1	SAR	SLCI	25303	2763	17-MAY-1996	09:46:15	+41:50	015:02
322203	E1	SAR	SLCI	24072	2763	21-FEB-1996	09:49:07	+41:50	014:19
322204	E1	SAR	SLCI	30585	2763	21-MAY-1997	09:48:57	+41:50	014:19
322205	E2	SAR	SLCI	12415	2763	04-SEP-1997	09:49:01	+41:50	014:19
322206	E2	SAR	SLCI	12916	2763	09-OCT-1997	09:49:02	+41:50	014:19
322207	E2	SAR	SLCI	5630	2763	18-MAY-1996	09:46:15	+41:50	015:02
322208	E2	SAR	SLCI	6632	2763	27-JUL-1996	09:46:13	+41:50	015:02
322209	E2	SAR	SLCI	4399	2763	22-FEB-1996	09:49:07	+41:50	014:19
322210	E2	SAR	SLCI	10912	2763	22-MAY-1997	09:49:02	+41:50	014:19
322211	E2	SAR	SLCI	6904	2763	15-AUG-1996	09:49:02	+41:50	014:19
Second dataset									
PJIDPJ	Sat	Sensor	Prod	Orbit	Frame	Acq. Date	Acq.Time	Lat	Long
325963	E1	SAR	SLCI	23070	2763	13-DEC-1995	09:49:07	+41:50	014:19
325964	E1	SAR	SLCI	40104	2763	17-MAR-1999	09:48:48	+41:50	014:19
325965	E1	SAR	SLCI	40333	2763	02-APR-1999	09:45:57	+41:50	015:02
325966	E2	SAR	SLCI	20431	2763	18-MAR-1999	09:48:57	+41:50	014:19
325967	E2	SAR	SLCI	20660	2763	03-APR-1999	09:46:05	+41:50	015:02

was necessary to submit another request in order to obtain good interferometric pairs (second dataset in tab. 4).

5.2 Ancillary data

The following data were adopted for the preliminary analysis of the landslide:

- Aerial photography 1992 / image scale 1:13000
- Aerial photography 1996 / image scale 1:8000 (acquired just after the event)
- Aerial photography 1997 / image scale 1:5000
- Numerical maps 1:25000/1:10000/1:5000/1:1000 (pre-event)
- Numerical map 1:1000 (post-event)
- High resolution/accuracy Digital Elevation Model (pre/post-event)

5.3 Interferometric Dataset

The available images of ERS-1 and ERS-2 descending orbits acquired between May 1996 and April 1999 allowed to obtain 12 interferometric pairs potentially useful for this study, and indicated in tab. 5. In order to indicate the relevance of the computed interferograms, the level of coherence between two epochs was qualitatively determined, as shown in

Table 5: Interferograms processed over the Covatta test site.

	IMAGE PAIRS	Comments		IMAGE PAIRS	Comments
1	13 dic 95 – 21 feb 96	Low coherence	*7*	15 ago 96 – 21 mag 97	Missing line
2	13 dic 95 – 22 feb 96	Low coherence	*8*	15 ago 96 – 22 mag 97	Very low coherence
3	21/22 feb 96	Good coherence	*9*	21/22 mag 97	Missing lines
4	17/18 mag 96	Orbital errors	*10*	4 set 97 – 9 ott 97	Low coherence
5	17 may 96 – 27 jul 96	Orbital errors	*11*	2/3 apr 99	Good coherence
6	18 mag 96- 27 lug 96	Very low coherence	*12*	17/18 mag 99	Good coherence

tab 5. Coherence levels are generally quite poor over the study area for pairs acquired more than 35 days apart. Thus, it was not possible to use all the available interferometric sets. Only the tandem pairs exhibit sufficient coherence levels for "conventional" DInSAR processing techniques. Therefore, the analysis was concentrated on 3 tandem pairs (number 3, 12 and 11 in tab. 5).

5.4 Interferometry and Differential Interferometry

Differential phase maps were obtained using the 3 coherent tandem pairs by removing the topographic component estimated from an external DEM (in the 2-pass mode) or from the interferometric DEM (in the 3- and 4-pass modes). The 2-pass mode was performed with the tandem pair 21-22/Feb/1996 and the DEM obtained from the Regione Molise, while the 4-pass mode with the tandem pair 17-18/Mar/1999 as differential pair and the tandem pair 2-3/Apr/1999 to derive the topographic information. The 3-pass was not performed because it was not possible to obtain a triplet of image with a good level of coherence.

The tandem pair acquired in April 1996 allowed to investigate the area before the major landslide, which occurred 50 days later. The differential interferogram and the coherence map were jointly analyzed in order to establish the presence of precursor activity (see fig. 7). The anomalies which can be observed in the interferogram as colored patches at the top of the slope, could be caused by non-homogeneous displacements. At the same time, strong decorrelation is present in the coherence map over the same area. These two facts can be ascribed to the same phenomenon and imply the occurrence of sensible variation in the backscattering centers. In other words, this situation may be indicating the presence of preparatory activity in the upper part of the landslide before the paroxystic stage. The absence of fringes or anomalies on the landslide body indicates that no other movements were present.

The analysis of the dataset including the tandem pair 17-18/Mar/1999 and the DEM derived from the tandem pair 2- 3/Apr/1999 allows to detect and quantify the displacements occurring at recent times (the landslide is still active). In fig. 8, the landslide body is clearly identifiable where the green colour, which characterizes the whole area, abruptly turns into a dark blue and then into red. The most active areas correspond to the toe area and to the top of the flow channel, as confirmed by the deformation pattern extrapolated from a topographic survey performed in the same period. Furthermore, on the same differential interferogram, another area potentially affected by a slope instability is visible (see fig. 9). This area was later precisely localized and identified with a landslide re-activated in 1998 (The Gallo landslide).

6 CONCLUSIONS

The application of InSAR data to slope stability studies, which most commonly involve relatively small areas (up to a few km^2), is limited by environmental conditions. These problems are demonstrated by the results of the two case-studies shown in this work, where an assessment of the possibilities and performances of DInSAR techniques for landslide monitoring has been performed.

DInSAR data have been matched with ground truth data available over two landslide test sites in Italy. Although it was not possible to take advantage of all the available images, due to low coherence problems, some results appear compatible with ground monitoring data. In the case of the Central Italy (Covatta) test site, the results obtained from the

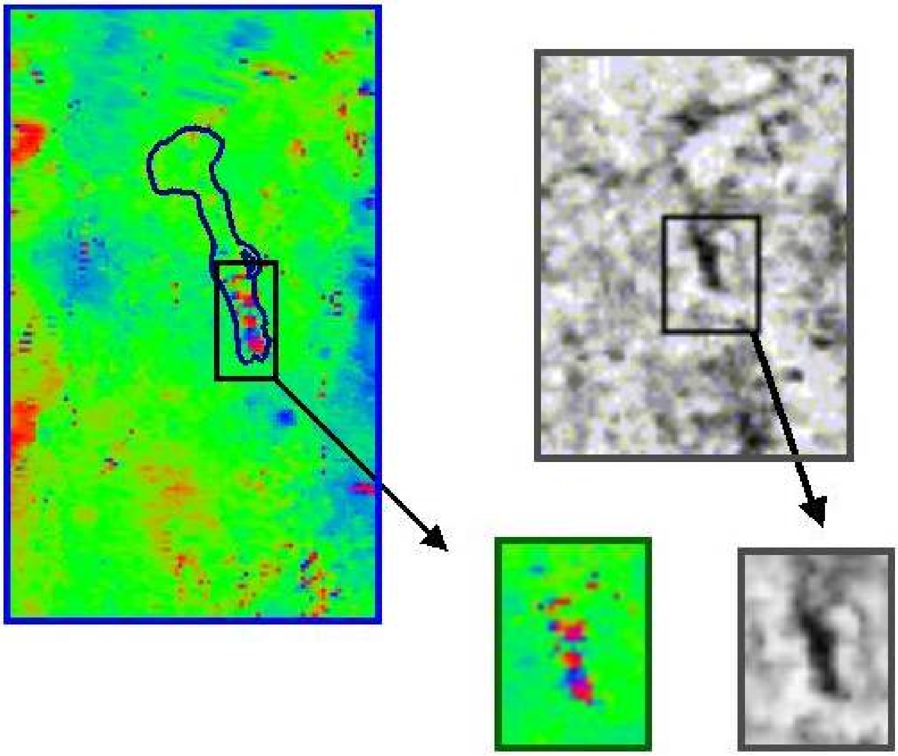


Figure 7: Differential interferogram pre-landslide derived by the 21-22/Feb/1996 tandem pair using an external DEM to remove topography.

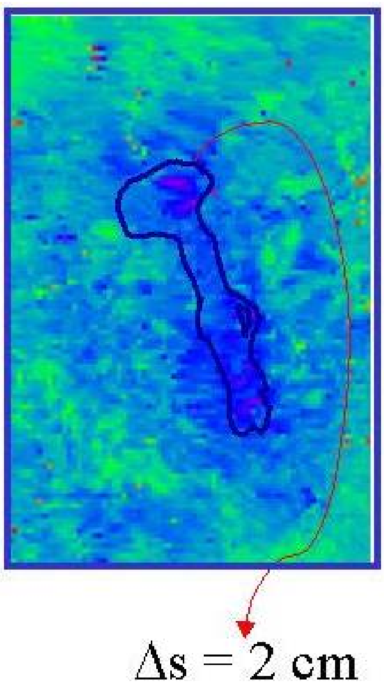


Figure 8: The Covatta landslide area in the differential interferogram post-landslide (17-18/Mar/1999 tandem pair).

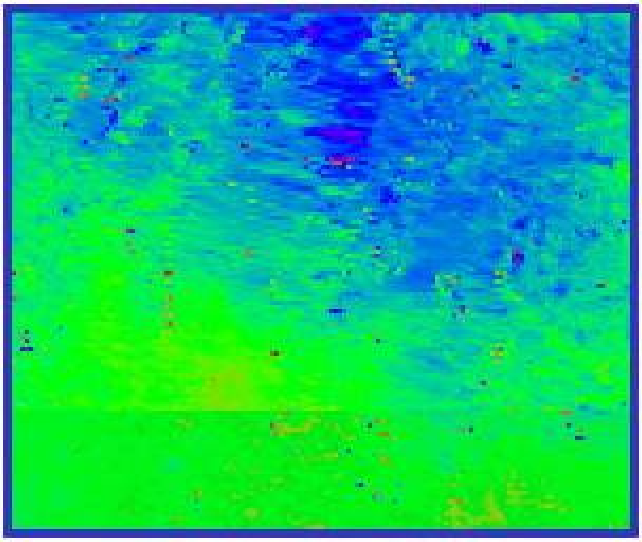


Figure 9: The Gallo landslide area in the differential interferogram post-landslide (17-18/Mar/1999 tandem pair).

analysis of the images collected before the landslide re-activation allowed to generate an *a priori* digital terrain model and to detect precursory movements. The dataset acquired after the major event were initially adopted for contouring the area affected by the landslide and generating a post-event digital terrain model. On one interferometric tandem pair it was possible to localize and quantify the displacements along the landslide and to observe an nearby undetected landslide. In the Southern Italy test site (Senerchia), innovative processing techniques are being developed and applied to the available dataset. Techniques taking into account all the possible contributions to the phase signal (movement, DEM error, noise, and atmospheric effects), and relying on the stability of particular objects, such as the "permanent scatterers" method, appear necessary to extract reliable information for the area affected by slope movements. In this work, a preliminary PS processing, applied to a rural area, has been described. Results show a good spatial density of candidate PS locations, which encourage to pursue a better assessment of the limits and potential of such a technique over areas with low number of man-made features.

Future developments may include the application of the same type of analysis to other similar sites and to landslides with different characteristics. In order to

promote the application of these techniques to an operational level at regional scale, which implies evaluation of slope stability in non-monitored areas, further tests and standardization of the processing appear necessary.

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