Geomorphology 223 (2014) 45–60

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Integration between ground based and satellite SAR data in landslide mapping: The San Fratello case study

Federica Bardi [a,*], William Frodella [a], Andrea Ciampalini [a], Silvia Bianchini [a], Chiara Del Ventisette [a], Giovanni Gigli [a], Riccardo Fanti [a], Sandro Moretti [a], Giuseppe Basile [b], Nicola Casagli [a]

[a] Earth Science Department, Università di Firenze, via La Pira 4, Firenze 50121, Italy
[b] Dipartimento Regionale della Protezione Civile, Regione Siciliana, Servizio Rischi Idrogeologici e Ambientali, via Abela 5, Palermo 90141, Italy

ARTICLE INFO

Article history:
Received 5 February 2014
Received in revised form 12 June 2014
Accepted 13 June 2014
Available online 6 July 2014

Keywords:
Satellite interferometry
Ground-based radar
PSI
Landslide mapping
Ground deformation
SAR data integration

ABSTRACT

The potential use of the integration of PSI (Persistent Scatterer Interferometry) and GB-InSAR (Ground-based Synthetic Aperture Radar Interferometry) for landslide hazard mitigation was evaluated for mapping and monitoring activities of the San Fratello landslide (Sicily, Italy). Intense and exceptional rainfall events are the main factors that triggered several slope movements in the study area, which is susceptible to landslides, because of its steep slopes and silty–clayey sedimentary cover.

In the last three centuries, the town of San Fratello was affected by three large landslides, developed in different periods: the oldest one occurred in 1754, damaging the northeastern sector of the town; in 1922 a large landslide completely destroyed a wide area in the western hillside of the town. In this paper, the attention is focussed on the most recent landslide that occurred on 14 February 2010: in this case, the phenomenon produced the failure of a large sector of the eastern hillside, causing severe damages to buildings and infrastructures. In particular, several slow-moving rotational and translational slides occurred in the area, making it suitable to monitor ground instability through different InSAR techniques.

PS-InSAR™ (permanent scatterers SAR interferometry) techniques, using ERS-1/ERS-2, ENVISAT, RADARSAT-1, and COSMO-SkyMed SAR images, were applied to analyze ground displacements during pre- and post-event phases. Moreover, during the post-event phase in March 2010, a GB-InSAR system, able to acquire data continuously every 14 min, was installed collecting ground displacement maps for a period of about three years, until March 2013. Through the integration of space-borne and ground-based data sets, ground deformation velocity maps were obtained, providing a more accurate delimitation of the February 2010 landslide boundary, with respect to the carried out traditional geomorphological field survey. The integration of GB-InSAR and PSI techniques proved to be very effective in landslide mapping in the San Fratello test site, representing a valid scientific support for local authorities and decision makers during the post-emergency management.

1. Introduction

Landslide mapping in the field is often a quite complex task; this can be owing to (i) the size of the landslide, often too large to be completely observed in the field; (ii) the viewpoint of the investigator, often inadequate to see all parts of a landslide (e.g., the scarp, lateral edges, deposit, toe) with the same detail; or (iii) the fact that old landslides are often partially or totally covered by vegetation or have been partly dismantled by other landslides, erosion processes, and human actions, including agricultural and forest practices (Guzzetti et al., 2012). The reduced visibility of the slope failure makes it difficult to accurately follow a landslide boundary in the field: this is a consequence of the local perspective of the size of the landslide and of the fact that the landslide boundary is often indistinct.

Thus, the perspective offered by a distant view of the landslide is preferable and can result in more accurate and more complete landslide mapping (Guzzetti et al., 2012).

In this paper, an improvement of the 2010 San Fratello landslide map was performed through the use of radar interferometry, specifically integrating the Persistent Scatterer Interferometry (PSI) with the Ground-based Synthetic Aperture Radar Interferometry (GB-InSAR).

The PSI is a well-known powerful and advanced multitemporal interferometric SAR technique, which allows measuring centimetric and subcentimetric ground displacements occurring during a defined range of time with millimeter accuracy (Ferretti et al., 2001). This work fully exploits both the satellite systems operating in the microwave C-band (i.e., ERS 1/2, ENVISAT, and RADARSAT-1 interferometric archives) and

* Correspondig author at: via La Pira 4, Firenze 50121, Italy. Tel.: +39 055 2757777; fax: +39 055 2757788.
E-mail address: federica.bardi@unifi.it (F. Bardi).

http://dx.doi.org/10.1016/j.geomorph.2014.06.025
0169-555X/

new generation SAR data acquired in X-band by the recent space missions, such as COSMO-SkyMed. The analysis of the benefits introduced by the aforementioned new satellite missions, in terms of technical performances and improvements in applications, was here investigated.

The GB-InSAR is a powerful terrestrial technique, widely used in engineering and in geological applications to detect the target (structure and ground) displacements (Casagli et al., 2002; Tarchi et al., 2003a; Noferini et al., 2007; Casagli et al., 2009; Herrera et al., 2009; Casagli et al., 2010; Del Ventisette et al., 2011). A GB-InSAR is a ground-based system that works with the same principles as space-borne sensors for monitoring ground deformation phenomena.

The interferometric technique is based on a comparison between two SAR images acquired at different times; this permits evidence of eventual displacements occurring during the time span between the two acquisitions. The time necessary to the sensor to realize two subsequent acquisitions is connected to the range of displacement velocities that the instrument can recognize. Therefore, satellite data are useful in monitoring extremely or very slow movements, whereas the GB-InSAR devices allow the assessment of ground deformations of faster landslides, thanks to the possibility of realizing higher frequency measurements (Corsini et al., 2006; Noferini et al., 2008). In addition, the spatial coverage of satellite data is limited by the SAR imaging geometry caused by layover, foreshortening and shadowing effects (Ferretti et al., 2001). A GB-InSAR, on the other hand, also can be placed in front of steep slopes, which are in most cases not visible from space-borne platforms.

The PSI and GB-InSAR work at different spatial and temporal scales. Because of the above-mentioned characteristics and differences, the integration of these techniques enables us to obtain useful information on the ground displacement measurements, with high precision and improved spatial and temporal resolution. In particular, the use of PSI allows performing a preliminary study on ground displacements at a basin scale, providing hotspot mapping (which can be useful prior to planning a GB-InSAR system installation for a monitoring campaign) over a specific area affected by landslides.

Between the end of 2009 and the beginning of 2010, the Nebrodi Mountains (western Sicily, Italy) were highly affected by several landslide events causing intense damages and casualties. Some of these landslides are still active at present day. Intense and exceptional rainfall events (about 900 mm in the period between October 2009 and January 2010) were the main factor that, combined with the strong topographical relief, triggered several slope movements. In this work, the PSI and GB-InSAR techniques were qualitatively integrated in order to improve the 2010 landslide map. The satellite data, measured along the satellite Line Of Sight (LOS), were projected on the slope direction, providing the component of the velocity registered by the sensors on the direction of the slope (V_{slope}). The line of sight of the GB-InSAR system is quite similar to the slope direction, so the displacements registered in this direction are comparable to the projected satellite data.

A list of the used satellite data is shown in Table 1 together with the characteristics of the sensors. The GB-InSAR data were recorded during the monitoring campaign, realized between March 2010 and March 2013: in this period the instrument generated interferograms continuously, every 14 min.

The integration was based on a binary approach to divide the areas characterized by displacements from the ones without displacements. The method was validated comparing the results with the evidence of the damage assessment map produced by the Department of Civil Protection (Fig. 5) and on the basis of the results of field trips, which allowed us to detect soil fractures and landslide scarps (Figs. 4C and 5). The integration was used to update the map of the San Fratello landslide.

2. Geomorphological and geological framework

The town of San Fratello is located in northeastern Sicily, Italy (Messina Province, Fig. 1B), on the northwestern hillside of the Nebrodi Mountains (Fig. 1A), a 70-km-long ridge with an ENE–WSW direction, within the southern Apennine chain.

The geomorphology of the study area shows the typical features of the Sicilian Tyrrhenian coastline: steep slopes rise abruptly from the coastal plain and are deeply cut by N–NW-directed creek valleys (called *fiumare*). In this context, the town of San Fratello is located about 5 km south of the seaside, on a divide separating the Furiano Creek valley to the west from the Inganno Creek valley to the east (Fig. 1C).

From a geological point of view, the study area is part of the northeastern sector of the Apennine–Maghrebian orogenic belt, and it is characterized by the tectonic overriding of the uppermost Kabilian-Calabrid units, consisting of dolomitic limestones and sandstones (Fig. 2A, B), formed in this area mainly by marlstone and claystone formations (Ogniben, 1960; Atzori and Vezzani, 1974; Lentini and Vezzani, 1975; Atzori et al., 1978; Lentini et al., 1990, 1994, 1995; Finetti et al., 1996; Lentini et al., 2000). This geological framework determines the overlapping of geological formations with marked differences in geotechnical properties, deeply influencing the study area landscape and slope instability phenomena: hilltops, made of hard-brittle lithologies, are undermined by the weathering and erosional processes taking place in the underlying soft clayey formations. In the San Fratello area, on the top of the bedrock, a silty–clayey cover lies with an average thickness of about 10 m; the 2010 landslide affected this layer, involving all the thickness or the biggest part of it, with a surface rupture 8–10 m deep (Pino et al., 2010). The low quality of the geotechnical properties of this layer probably played an important role in the landslide trigger, together with the steep slope angle (more than 30°) and the intense precipitation events of the period. In particular, the period between October 2009 and January 2010 recorded more than 900 mm of precipitation (Fig. 3). The area was impacted by other similar phenomena in the past; in 1754, a large landslide damaged the northeastern sector of

Table 1
Characteristics of the satellites used for the PS-InSAR monitoring of the San Fratello landslide.

Satellite	ERS 1/2	ERS 1/2	ENVISAT	ENVISAT	RADARSAT-1	RADARSAT-1	COSMO-SkyMed
Band	C	C	C	C	C	C	X
Geometry	Ascending	Descending	Ascending	Descending	Ascending	Descending	Descending
Repeat time (days)	35	35	35	35	24	24	4
Temporal range	11/09/92–05/06/00	01/05/92–08/01/01	22/01/03–22/09/10	07/07/03–13/09/10	30/12/05–04/09/09	31/01/06–06/10/09	16/05/11–02/05/12
N° scenes	34	70	65	49	46	47	32
PS/km^2	6.55	2.25	64.74	20.41	112.73	86.86	400.62
Spatial accuracy (m)	±4–±10	±4–±10	±4–±10	±4–±10	±4–±8	±4–±8	±3
0 ± dev. stand. (mm/y) (0 ± σ)	0 ± 2.5	0 ± 1.7	0 ± 2.1	0 ± 1.5	0 ± 2.5	0 ± 2.1	0 ± 3.7
LOS vel. range (min, max) (mm/y)	−9.5, +7.2	−26.8, +8.6	−39.3, +10.1	−22.5, +5.9	−46.8, +19.8	−26.3, +20.5	−56.4, +31.8
Mean LOS vel. (mm/y)	−0.5	−0.4	0.0	−0.6	−0.4	0.0	−1.0