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Ground-Based Radar Interferometry for Landslide Monitoring

Nicola Casagli, Filippo Catani, Chiara Del Ventisette and Guido Luzi

Abstract

Landslide detection and monitoring represent a starting point to produce hazard and risk maps useful to define adequate prevention measures and to manage landslide emergencies. This paper reports the experience of our research group on the ground-based synthetic aperture radar interferometry. In particular, we discuss the use of a ground-based synthetic aperture radar interferometer (GB-InSAR) not only as a monitoring system but also as a tool to obtain spatial information on the landslide displacements to be integrated with rainfall data. This technique can be incorporated in an early warning system for the detection of slope acceleration patterns indicating the upcoming occurrence of a slope failure. The case studies reported demonstrate the capability of this technique to operate in different operative settings (i.e., different phenomena and geological framework) and for different aims (monitoring for prevention, early warning, and emergency assessment). This methodology has also been proved by national and regional authorities of civil protection in order to provide a real-time monitoring for emergency management.

Keywords

Landslides · Interferometry · Ground-based SAR
Ruinon (Valfurva, Italy) · Stromboli (Italy)

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Contents

1 Introduction

Landslide represents one of the major natural hazards causing fatalities and economic damage worldwide. Their detection and real-time monitoring, that considers the triggering factors and landslide kinematics, represent a starting point to produce hazard and risk maps useful for a proper urban planning and to define adequate prevention measures for the mitigation of loss of human life and of assets. The remote sensing approach allows obtaining the two-dimensional deformation maps can overcome some limitations of early warning system based on in situ instrumentation (i.e. provides measurements obtained in a few points of the monitored area, which are often not adequately representative of the whole unstable area).

The GB-InSAR is a remote sensing technique based on microwaves interferometry which permits, starting from two or more images, the production of 2D displacement maps of a region (also called interferograms) with millimetre precision.

The used GB-InSAR has metre-scale spatial resolution and an acquisition frequency variable between 5 and 11 min. Interferograms, that does not contain topographic information, since the position of the antennas remains the same during different scans (zero baseline condition), are obtained using pairs of averaged sequential images. Through the phase difference of the backscattered signal in different times, it is possible to estimate the displacement (it is possible to assess only the component of the displacement vector along the line-of-sight—LoS); minus and positive signs indicate movement towards and away from the sensor, respectively.

This technique has been used in a variety of applications from landslide early warning and investigation (Tarchi et al. 2003; Del Ventisette et al. 2011, 2012; Intrieri et al. 2013; Bardi et al. 2014; Tofani et al. 2014) to civil engineering applications (Tarchi et al. 1997), glacier monitoring (Strozzi et al. 2012) and snow characterization (Luzi et al. 2009).

2 A Monitoring Case: Ruinon Landslide (Valfurva, Italy)

The example chosen to show the application of GB-InSAR technique to monitor active landslide is the Ruinon landslide, which is a 30 × 106 m^3 active rock slide located on the North-East sector of the Valfurva valley (Fig. 1). A potential risk from this landslide, which is suspended above the valley, is the possibility of a fast-moving rock avalanche affecting the important tourist road connecting Bormio to Santa Caterina Valfurva and the consequent development of a strongly unstable landslide dam on the Frodolfo River.

The landslide that affects a steep slope made by schistose metapelites locally covered by slope debris (Agliardi et al. 2001; Tarchi et al. 2003). From a geomorphological point of view the landslide is characterized by two main scarps oriented northwest–southeast, parallel to the main fracture system recorded on the slope.

Geological aspects of Ruinon landslide were thoroughly analyzed by several authors (Agliardi et al. 2001; Crosta and Agliardi 2003; Tarchi et al. 2003 cum biblio).

Since 1997 a permanent monitoring network (total station, GPS receivers, inclinometer tubes and extensometers) has been installed by the ARPA.

The first ground-based SAR interferometric measurement campaign about this landslide dates back to summer 2000 (Tarchi et al. 2003; Antonello et al. 2004). In June 2006, a permanent

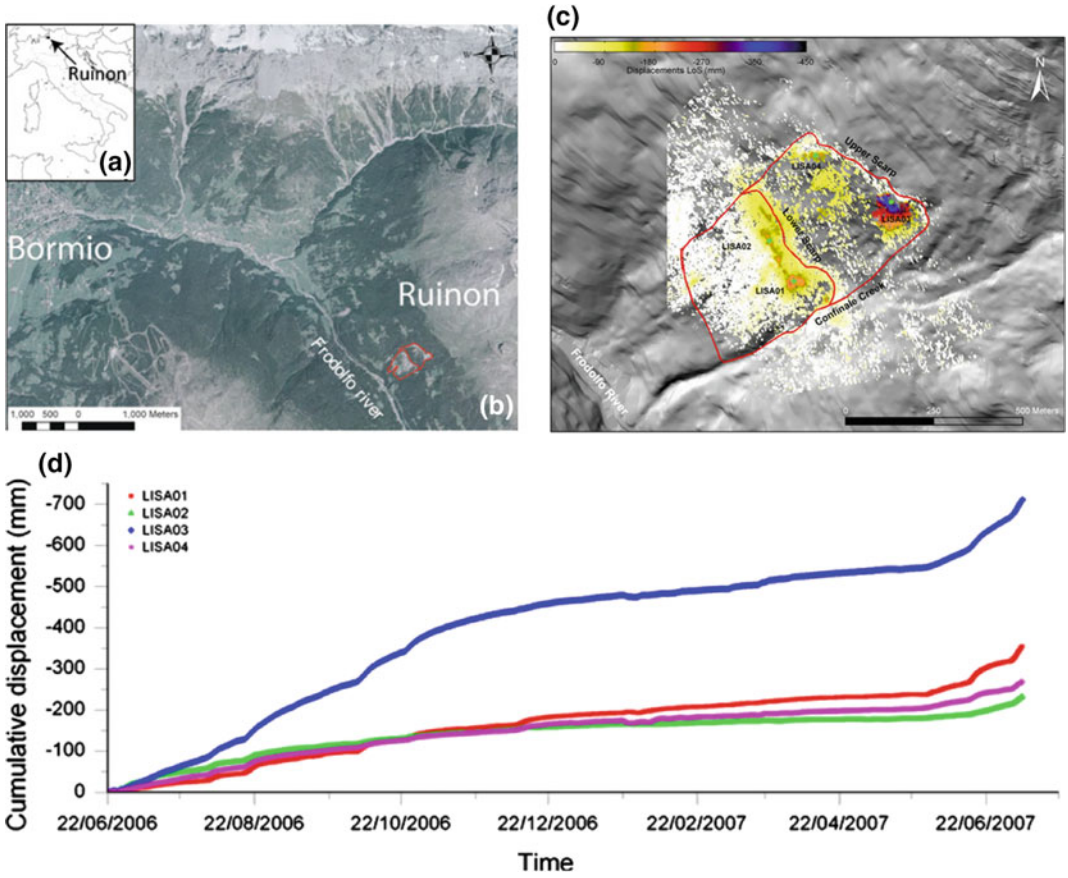

Fig. 1 **a**, **b** Location of the Ruinon landslide. The Ruinon landslide developing in the Valfurva Valley on the hydrographic right of the Frodolfo river. **c** Cumulative displacement map spanning a period of 364 days, 14 h and 50 min between 22/06/2006 and 22/06/2007. LISA01, LISA02, LISA03, and LISA04 identify the points whose displacement-time diagram are plotted in **d**

GB-InSAR monitoring system was installed for early warning purposes.

The acquired data have permitted evaluation of the capability of the apparatus to detect the movement of the landslides' surface and to integrate them with data coming from in situ instrumentations, allowing arrangement of early warning systems.

2.1 Data Analysis

In this paper results of the GB-InSAR monitoring from June 2006 to June 2007, are briefly presented. Thanks to the high sampling rate of the GB-InSAR system, multitemporal maps showing the complete displacement field of the landslide have been generated and used to derive velocity–time diagrams for selected pixels.

The analysis of cumulative displacement maps in a quasi-continuous surface allows identification of landslide sectors characterized by different displacement patterns, indicating partial activations or site-specific surface processes.

The deformations are mainly focused on two sectors (Fig. 1b); (i) the eastern part of the Upper Scarp (total estimated displacement along LoS for the entire period of monitoring is more than

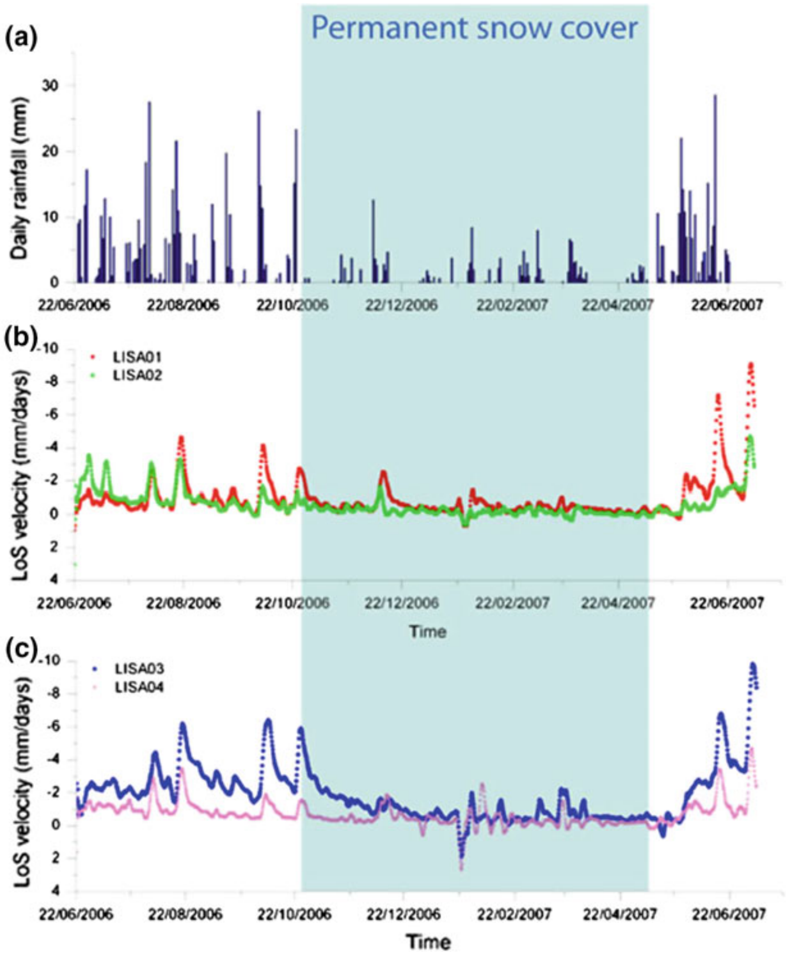

Fig. 2 Comparison among rainfall events (daily rainfall and cumulative rainfall) and velocity displacement as a function of time. **a** Daily rainfall; **b** LOS velocity versus time diagram of the point located on the *Lower Scarp* (LISA01 and LISA02); **c** LOS velocity versus time diagram of the points located on the *Upper Scarp* (LISA03 and LISA04)

630 mm, Fig. 1c), and (ii) the upper sector of the Lower Scarp (total displacement along the LoS more than 300 mm, Fig. 1c).

The cumulative displacement versus time shown a clear seasonality with the maximum speed recorded in spring and the minimum recorded during the winter. These plots demonstrate that the seasonal accelerating phase is generally rapid and followed by a slower deceleration phase.

The area is characterized by a typical continental-alpine rainfall regime (with rainy summer and autumn).

The data recorded by the GB-InSAR show a good correlation between landslide acceleration peaks and rainfalls (Fig. 2).

The recorded acceleration peaks are mainly located after major rainfall events (defined as the occurrence of two o more rainy days separated by at least 2 days with rainfall <4 mm). Although the water amount resulting from snow melting, which of course occurs later than precipitation, has not been taken into account in this analysis, is possible to clearly distinguish the effects of rainfall on the landslide.

3 Monitoring and Early Warning at Stromboli

As example of the capability to use the GB-InSAR system as continuous and long-tome monitoring system we present the Stromboli case study, a composite volcano forming the northernmost island of the Aeolian Archipelago (Tyrrhenian Sea; Fig. 3).

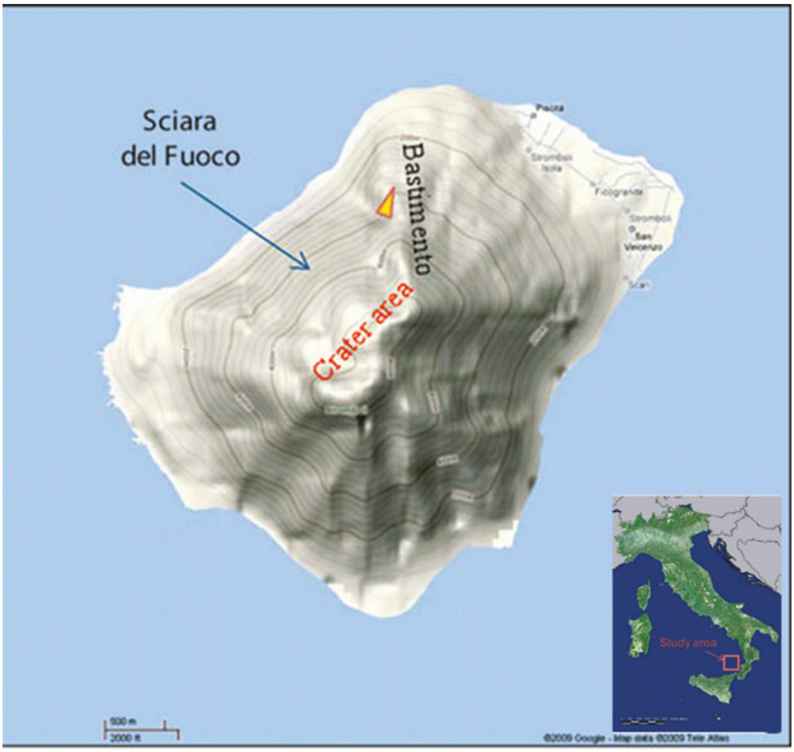

Fig. 3 Localization of: **a** Stromboli volcano and **b** Sciara del Fuoco. The *yellow triangle* in **b** marks the radar site

In this site, during the last 13 years, the GB-InSAR technique has disclosed its reliability and robustness in a real operational case (Barbieri et al. 2004; Bertolaso et al. 2009; Casagli et al. 2009; Tarchi et al. 2009; Di Traglia et al. 2013, 2014a, b).

Although the activity of Stromboli volcano is generally characterized by a persistent mild explosive activity at the summit craters, in the last 13 years, the usually mild "Strombolian" activity of the volcano has been interrupted by instability periods that influenced the stability of the Sciara del Fuoco landslide (SdF). From February 2003 GB-InSAR system was operative to monitor the crater area and the SdF (Bertolaso et al. 2009; Tarchi et al. 2009 cum biblio; Nolesini et al. 2013; Di Traglia et al. 2014b) with the aim to understand triggering mechanisms and dynamics of the SdF slope and, applying forecast methods as those proposed by Fukuzono (1985a, b, 1990) and Voight (1988, 1989, 2000), to built a early warning system.

The static loading induced by the continuous deposition of lava at the top of the SdF, the increased magma pressure inside dykes, and the dynamic loading caused by explosions and eruptive processes appear to be the main causes of the landslide initiation.

The presence of lava flows along the unstable slope inhibited the use of traditional topographic surveys, such as total stations and GPS receivers which require the access to the unstable slope for sensor placement. In this occasion, interferometric processing of spaceborne radar imagery, even if frequently applied to volcanoes monitoring (Amelung et al. 2000; Pritchard and Simons 2002), was not suitable for its satellites inadequate revisiting time, with respect to the velocity of the observed phenomena and for the geometric distortions induced by the SdF steepness.

The GB-InSAR data have been used both for long-term monitoring on areas with low displacement rates as the SdF (using interferograms calculated on long time intervals spanning from weeks to months) and for early warning studying explosions and rapid movements using interferograms calculated on relatively brief time intervals (spanning from a few minutes to a few days). The use of interferograms spanning a long time interval permits us to distinguish areas affected by different kinds of movement probably due to different triggering mechanism.

The capability of GB-InSAR instrumentation of reproducing the ground field of motion in a quasi-real time and in a detailed scale, allows the continuous monitoring of the deformational evolution of the volcano flank and consequently, the use of the system for early warning.

3.1 Data Analysis

In this paper we report some GB-InSAR data used as long-time deformation monitoring of SdF (2007–2012) and as early warning system (during the 2007 “crisis”).

Interferograms calculated over a time interval of 28 days over the entire period of monitoring (2003–2016) show the presence of two sectors on the SdF characterized by different deformation rate and geometry. For example, during December 2008, the upper sector of the SdF is characterized by two separate elongated, tongue-like movement patterns (Fig. 4). The lower sector displays higher displacement rates (0.23 mm/day); here the moving area is narrower and nail shaped. Moreover during this time a major explosion and a high intensity Strombolian explosion occurred, respectively on the 6th and the 17th of December, inducing a total decorrelation of the crater area.

From January 15th 2007, deformations on the crater area began to increase with respect to the low usual value measured in the “normal Strombolian activity”. On February 27th, the effusive phase occurred; it was characterized by an explosion in the lower sector of the crater

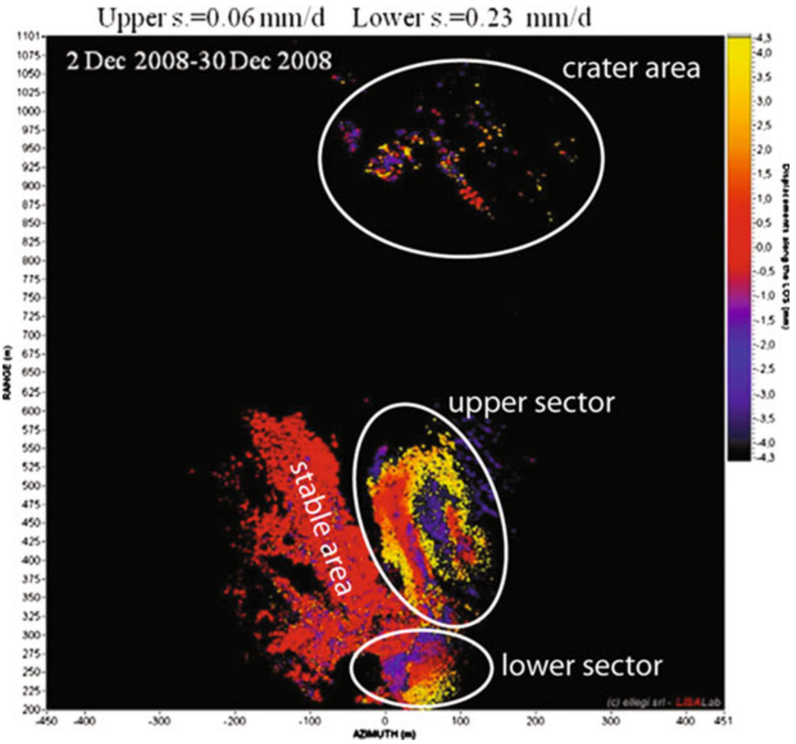

Fig. 4 Example of 28-day interferograms representative of the period 2–30 December 2008

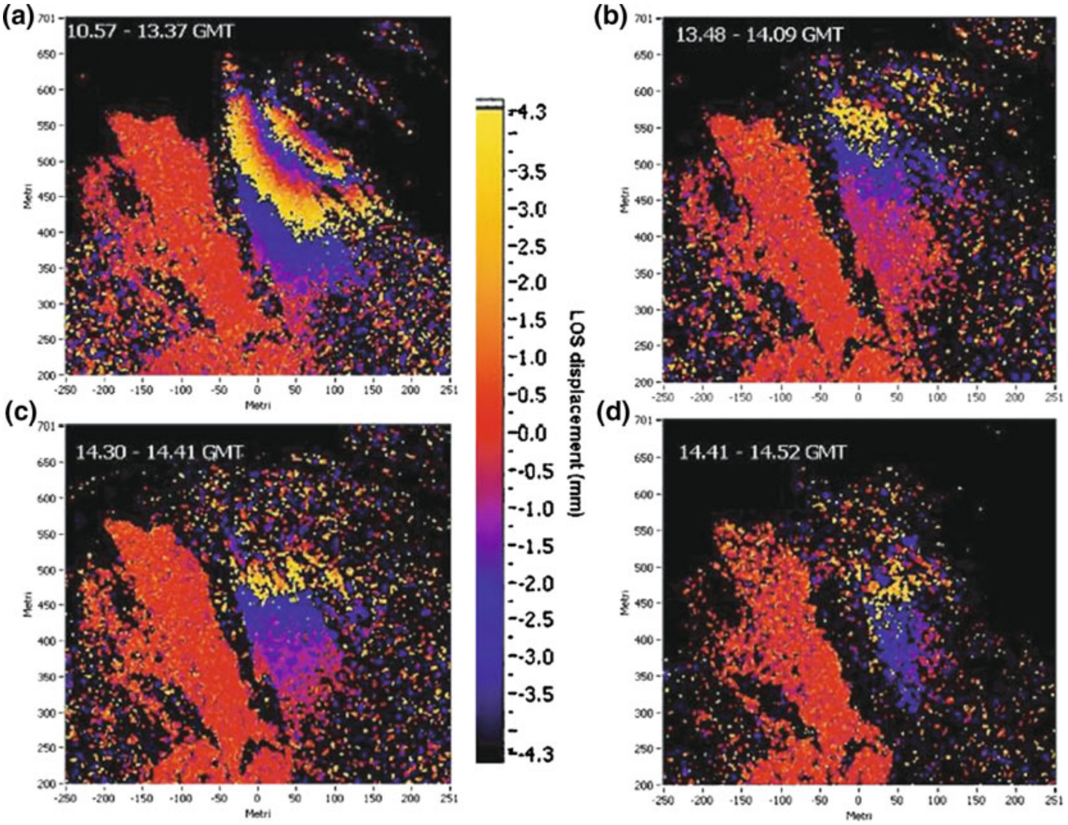

Fig. 5 Interferograms expressed through displacement map obtained on 27 February 2007, spanning different time intervals: **a** 10:57 GMT to 13:37 UT; **b** 13:18 UT to 14:09 UT; **c** 14:30 UT to 14:41 UT; and **d** 14:41 UT to 14:52 UT

area, which induced a partial collapse of the crater flank and was followed by the opening of a new vent at 600 mslm. This event induced inducing deformations also on the SdF.

The effect of these events can be clearly observed on the interferogram where the region corresponding to the craters appears totally decorrelated (see the "salt and pepper" texture) due to the rapidly occurred morphological modifications. Moreover, in the SdF portion of the map, a fringe is observable due to surface deformation related to the vent opening. An outline of the deformations occurring on the SdF on February 27th can be formulated in detail observing the sequence of interferograms in Fig. 5. In the first phase (10:57–13.37 UT), the interferometric fringes are parallel to the slope direction (Fig. 5a), suggesting a volcanic deformation on the flank. On the other hand, the direction of the fringes in the residual figures (Fig. 5b–d) is predominantly perpendicular to this direction, which can be interpreted as the signature of a gravitational movement towards the sea.

4 Discussion and Conclusions

This paper highlights the utility to use a ground-based interferometric SAR to monitor fast landslides and unstable slopes. The main characteristics of a GB-InSAR monitoring is to acquire information on the displacements over the entire observed area, permitting to gain information of dangerous and fast-moving areas, where no in situ instrumentation can been installed. As demonstrated in the Ruinon test site and in long-term monitoring of Stromboli, this features permits to identify the landslide sectors characterized by a different behaviour and also related to possible triggering mechanism.

The analysis of the Ruinon landslide kinematics, in particular, the abrupt acceleration phases, suggests a relation between acceleration peaks and rain.

The Stromboli test site has also demonstrated the system capability of being employed over long time periods, as a permanent monitoring system and also in presence of fast-evolution processes in unfavourable environmental settings. In particular, when there is a complex displacement pattern derived from the superimposition and interference of different processes (i.e., the deformation due to the lava flow and the bulging related to the opening of new vent superposed on that due to the slope instability), it is possible to understand the behaviour of the monitored portion of the SdF during particular events.

The accuracy of GBInSAR data in mapping and in monitoring landslides is fundamental in risk management and in preparation of emergency plans.

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