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## Abstract

Remote sensing techniques for the monitoring of displacements are opening new opportunities in the field of geotechnical engineering and geology. Terrestrial Synthetic Aperture Radar (SAR) interferometry (TInSAR) is one of the most innovative techniques and it promises to be a very effective solution, which will be extensively used in the near future. TInSAR is characterized by several interesting features such as: (i) high density of information; (ii) fully remote capability; (iii) long range capability; (iv) panoramic perspective; (v) spatially continuous efficacy and (vi) high accuracy. Thanks to these features, TInSAR has been used for investigation and diagnostic purposes (e.g. landslide and structural movement monitoring), and provided very useful data.

## Keywords

TInSAR • Interferometry • Displacement • Landslide • Structures

## 37.1 Introduction

Over the past decades, displacement monitoring has become an important tool for assessment of stability conditions for the control of many geological, geotechnical and structural

problems. Hence, it is now a common requirement to have various monitoring plans covering different aspects in large construction/infrastructure projects (e.g. tunnels, dams, highways). In other words, displacement data obtained through monitoring is considered one of the most useful

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information for understanding the behavior of ground/structures we are interacting. Monitoring of displacements is in fact now widely accepted and, quite often, is also imposed by authorities in charge of workers safety and by insurance companies. Several remote sensing techniques are today available for displacement monitoring issues. In this perspective, it is worth remembering main features related to these approaches: (i) they have “panoramic perspective”, i.e. they provide the opportunity for looking at the subject area with a wider perspective than contact systems; (ii) their use can be negatively affected by the presence of obstacles along the line of sight (vegetation, working machines etc.); (iii) they do not require direct interaction with the monitored object/area; (iv) they look at the superficial effect of the ground/structure deformation; (v) the accuracy is strongly site-specific.

By showing some real examples based on application of Terrestrial SAR Interferometry we aim to promote better appreciation of the use of displacement monitoring as a control tool and as an investigation and diagnostic tool. In other words, under certain conditions, the monitoring of displacement allows to derive information on the behavior of both natural and man-made structures that may be useful for both decision-making and design purposes.

### 37.2 Terrestrial SAR Interferometry

Terrestrial Synthetic Aperture Radar Interferometry (TInSAR, also referred as GBInSAR) is a ground based radar technique for the remote monitoring of displacements (Antonello et al. 2004; Luzi 2010; Mazzanti 2011; Mazzanti 2012). TInSAR is applied by using equipment made of a

linear rail and a radar sensor (Fig. 37.1). The sensor, moving along the rail during data acquisition, derives 2D SAR images. Then, by the interferometric technique (i.e. by comparing the phase signal difference of each pixel between two or more images collected at different times) displacements along the instrument line of sight (LOS) are derived. Hence, both colored images and time series of displacement of each pixel can be achieved (Fig. 37.2). Pixel resolution ranges from less than one meter to few meters, depending on the rail length and the sensing distance. The accuracy in displacement measurement may range from few decimal mm under ideal conditions (short term and short distance monitoring), to some mm in more complex conditions.

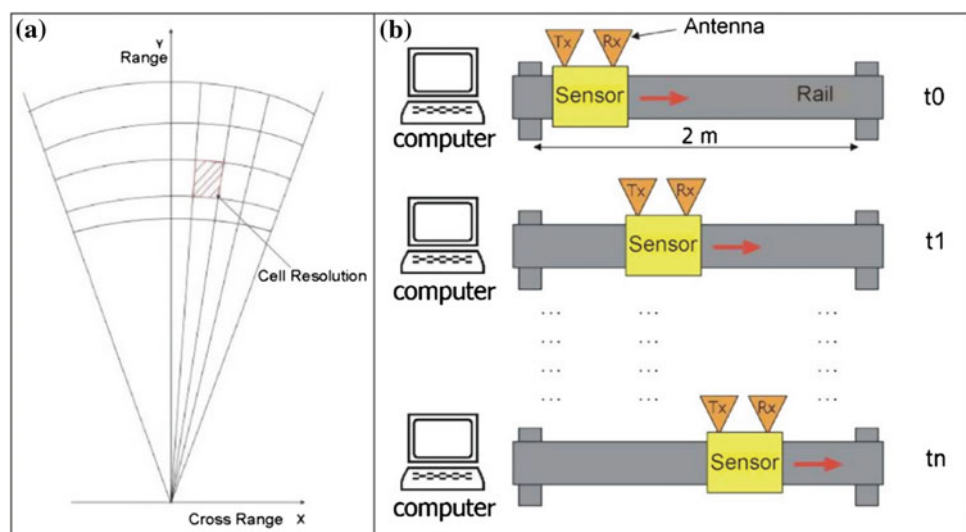
Depending on the equipment used, the temporal resolution (i.e. the data sampling rate) of SAR images may range from a few minutes to a few seconds. Furthermore, by using microwaves signals, TInSAR is able to collect data under any weather and lighting conditions.

TInSAR monitoring can be performed by installing the equipment in a stable location (up to 4 km away) with a panoramic view of the monitored area, and it does not require the installation of contact sensors or reflectors in the monitored area.

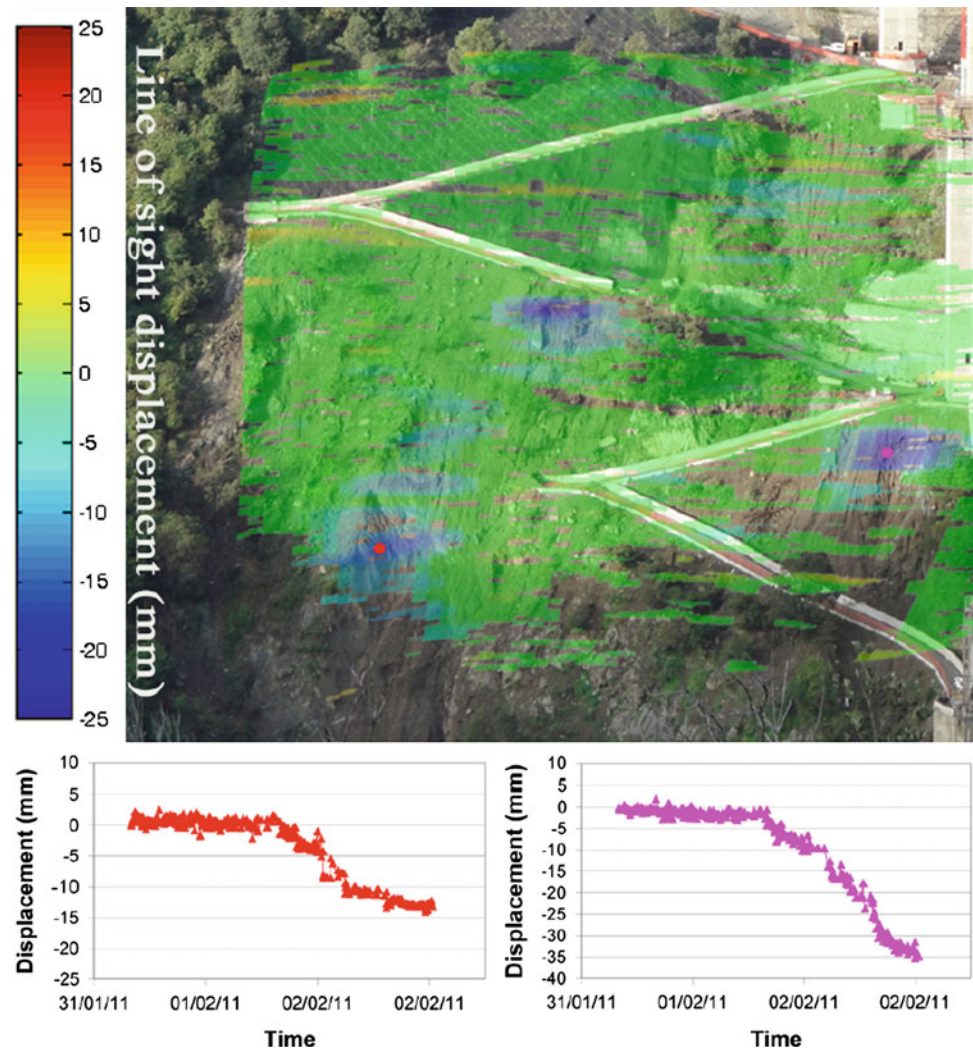
### 37.3 Investigation by Terrestrial SAR Interferometry

Over the past 10 years the authors have been following the development of the TInSAR technique from its early stage (i.e. the trial use of the first developed prototypes, to extensive and long-term applications by using industrial equipment). This long-term involvement allows the authors

**Fig. 37.1** Field of view sketch **a** and operational diagram, **b** of a TInSAR system



**Fig. 37.2** Displacement map overlaid to a slope picture and time series of displacement of two pixels



to build up experience in its use and to understand main advantages and limitations as well as efficacy in different applications of TInSAR. Specifically, the authors have been directly involved in projects concerning volcanoes, architectural heritages, civil buildings, dams, bridges, viaducts, tunnels, pipelines and several slope instability processes ranging from earth-flows, deep-seated rotational landslides, small translation landslides and rock cliffs instabilities (Bozzano et al. 2008, 2010, 2011; Mazzanti et al. 2011a; Mazzanti and Cipriani 2011).

In the early stage development of TInSAR technique, it was used mainly as an efficient safety control measures for continuous monitoring of instability processes which may generate risk to life and human activities (Casagli et al. 2003, 2010; Bozzano et al. 2011). For this application the following main features are required: (i) fully remote capability; (ii) accuracy in displacement measurement; (iii) high sampling rate; (iv) effectiveness under all weather and lighting conditions.

In recent years, TInSAR has demonstrated to be a powerful tool in the hands of geologists and geotechnical and structural engineers for investigation of ground and structural instability processes, thanks to same features described above, but also to: (i) the ‘panoramic view’ capability; (ii) the continuous spatial information; (iii) the high information density and long sensing distance.

Selected case examples of TInSAR monitoring for investigation purposes are described below.

### 37.3.1 Landslides

Landslides are probably the geological/geotechnical process which have been analyzed most extensively using Terrestrial SAR Interferometry (e.g. Antonello et al. 2004; Luzi 2010; Mazzanti 2011b).

In 2009, a slope affected by an earth flow, in the Lazio Region (Italy), was monitored continuously for one year

mainly as an emergency measures. A small portion of the slope, failed in the late 2008 following an intense rainfall. Due to the geological features, and due to heavy water ingress, the landslide debris at the lower part of the slope moved forward as an earth flow, hitting some houses and a major pipeline. The continuous monitoring using TInSAR, with a sampling rate of about 5 min, provided useful information on the slope behavior. Displacements collected on first day showed movements up to 40 mm along the 'Line of Sight' (LOS) in the deposit zone, while no movements were detected in the source area of the slope (Fig. 37.3). Hence, hazards were found to be mainly related to the flowing deposit, and no imminent retrogressive processes were going on.

Data collected during following days confirmed the stability of the up slope scarp and the movement of debris. Regarding the deposit, it was possible to depict a displacement behavior characterized by heterogeneous movements with accelerations and decelerations localized to small areas and a rapid response (i.e. acceleration) to rainfalls. Such a behavior was interpreted as the result of a superficial movement of the mass, which implies a low hazard to infrastructures.

In the authors experience, one of the most interesting applications of TInSAR is the monitoring of a complex deep-seated landslide affecting the entrance of an under construction tunnel in the southern part of Italy (Bozzano et al. 2008, 2011, 2012). Following the collapse of the tunnel portal during construction, a detailed investigation of the slope was carried out (Bozzano et al. 2011), thus allowing to achieve an engineering geology model of the slope and to design countermeasures for its stabilization. Furthermore, by

the combination of TInSAR data with other collected information, a detailed zoning of the whole slope was undertaken. However, the main contribution of TInSAR monitoring was the understanding of the overall transient behavior of the slope and its reaction to rainfalls and excavation activities. Specifically, by the back-analysis of more than 10 landslides (from 10 to 10,000 m<sup>3</sup>), occurred during the monitoring time, the main behavior of the slope, before failure, was derived (Mazzanti et al. 2011b). Suitable models for the prediction of landslides were also developed and calibrated (Bozzano et al. 2012), thus allowing the prediction of future events and the displacement to rainfall correlation to be derived.

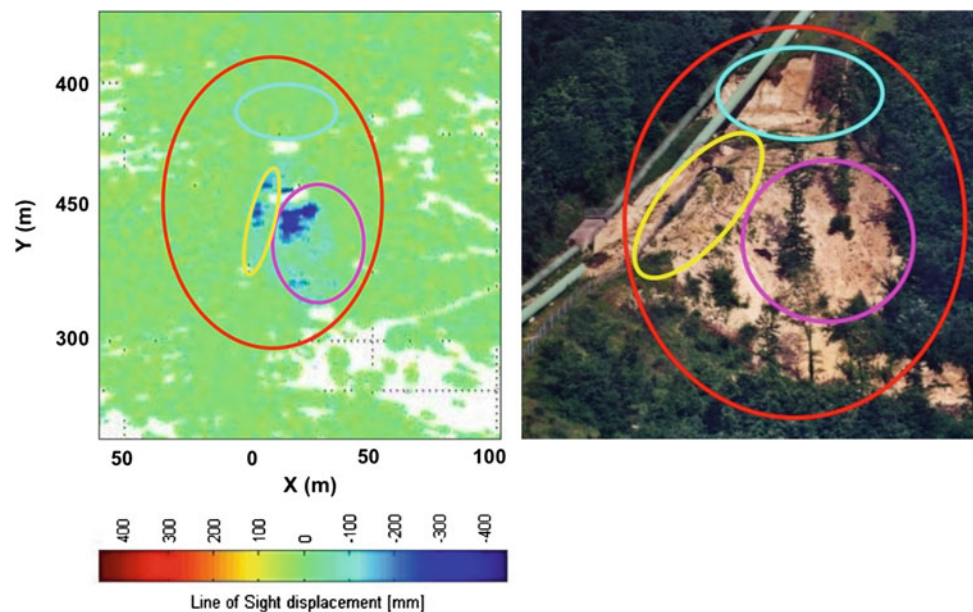
### 37.3.2 Rock Cliffs

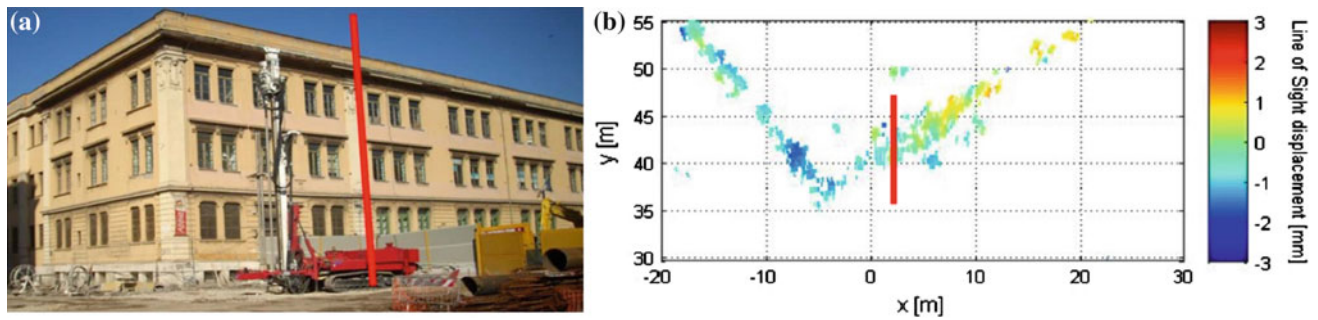
Recent studies have demonstrated that TInSAR may represent a useful tool to investigate stability condition of natural cliffs and that it is still more effective if combined with other remote and traditional techniques (Mazzanti et al. 2011a).

By monitoring vertical cliffs it is possible to identify sectors affected by permanent micro-movements (sometimes half a millimeter or less), which may indicate a fairly stable condition. Furthermore, by comparing TInSAR time series with temperature and rainfalls data it is possible to identify blocks affected by cyclic movements which can be assumed as the most susceptible to collapse.

This information may be very useful if combined with conventional investigation systems based on geomechanical analysis. As a matter of fact, conventional geomechanical

**Fig. 37.3** Picture of the landslide (*on the right*) and 24 h displacement map of 23-01-2009 (*on the left*). Colored ellipses identify corresponding sectors





**Fig. 37.4** Picture of the building and displacements map derived by TInSAR. The *red line* identifies the same sector

methods look only to preconditioning factors like joint features (orientation, spacing, aperture etc.), rock stiffness etc. On the other hand, information derived by TInSAR may provide useful indicators of the state of activity of a block by looking to its deformational behavior. Successful applications have been carried out by the authors on different cases in Italy over the past years (Mazzanti et al. 2011b).

### 37.3.3 Man-Made Structures

Remote monitoring of displacement of man-made structures by TInSAR may be very useful to complement conventional solutions. In what follows three examples are briefly presented.

A large road embankment in the Northern Italy affected by a severe instability has been monitored 24/7 with high accuracy and sampling rate in order to characterize the ongoing process and for workers safety purpose during the remediation activities. Embankment instability was detected in real time thus allowing identification of critical phases.

The precise mapping of sectors of a building affected by displacement may be derived from TInSAR monitoring thanks to its widespread coverage and spatially continuous capability. An interesting example refers to a civil building in the city of Rome, which was affected by displacements during the underground activities for the construction of the third Metro Line in Rome (Fig. 37.4) (Mazzanti and Cipriani 2011).

The rapid mapping of deformation pattern of a concrete or earth dam in response to increasing and decreasing of the water level may be easily derived by TInSAR monitoring. Furthermore, especially in the case of concrete dams with a sensing distance lower than 100 m, high accuracy (on the order of 0.1 mm) in the displacement measurement can be achieved.

## 37.4 Conclusions

To conclude, the here presented case studies demonstrate how TInSAR, represents a very effective solution to provide surficial displacements information in several contexts and for different needs. If compared with classical in situ and remote sensing monitoring techniques, TInSAR provides better results in terms of widespread information, accuracy (up to 0.1 mm), robustness and safety (no instruments installation is mandatory over instable areas).

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