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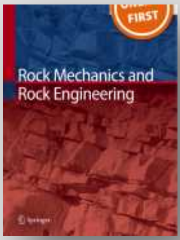

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Early warning monitoring of natural and engineered slopes with Ground-Based Synthetic Aperture Radar

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Abstract: The first application of ground-based interferometric synthetic-aperture radar (GBInSAR) for slope monitoring dates back 13 years. Today, GBInSAR is used internationally as a leading-edge tool for near-real-time monitoring of surface slope movements in landslides and open pit mines. The success of the technology relies mainly on its ability to measure slope movements rapidly with sub- millimetric accuracy over wide areas and in almost any weather conditions. In recent years, GBInSAR has experienced significant improvements, due to the development of more advanced radar techniques in terms of both data processing and sensor performance. These improvements have led to widespread diffusion of the technology for early warning monitoring of slopes in both civil and mining applications. The main technical features of modern SAR technology for slope monitoring are discussed in this paper. A comparative analysis with other monitoring technologies is also presented along with some recent examples of successful slope monitoring.

Keywords: Landslide, radar, monitoring, rock slopes

1. Introduction

The first application of ground-based interferometric synthetic-aperture radar (GBInSAR) for measurement of surface slope movements, by an Italian team of researchers in the Italian Alps, dates back to the year 2000 (Tarchi et al. 2003). Since that time, this technology has evolved from the prototype of the early days, composed of laboratory instrumentation temporarily used in the field, to an industrial product with the highest standards of quality in terms of both robustness and reliability. This progress has been due to the development of specific radar sensors and processing techniques dedicated to such applications.

In recent years, use of GBInSAR has become a common practice for monitoring landslides and open pit mines. The system is effectively used today for early warning monitoring to measure and predict the progressive movements that can lead to slope failure (Farina et al. 2012, 2013). This specific use takes advantage of the unique capabilities of radar to measure displacement and velocity very quickly (with acquisition frequency of a few minutes) over large areas (e.g. the entire face of a mine wall) with sub-millimetric accuracy and in almost any weather conditions without the need to install contact sensors on the slope.

These particular features, not offered today by any alternative monitoring technologies (at least to the same extent), are effectively used to support users in their decision-making processes, when the need arises to evacuate workers from an open pit mine or a built-up area threatened by an unstable slope. In addition, GBInSAR is capable of collecting quantitative information on slope behaviour from either a spatial or a temporal point of view. It provides, over long periods of time, accurate geo-referenced outputs and allows users to integrate radar data into geotechnical analysis of slope failure mechanisms.

In fact, GBInSAR data have been used to improve understanding of complex three-dimensional (3D) slope kinematics in open pit mines (Severin et al. 2011) and landslides (Barla et al. 2010a, 2011; Schulz et al. 2012). GBInSAR data have also been applied to predict the time of failure of unstable slopes (Casagli et al. 2010) and for validation of geotechnical models (Barla and Antolini 2012; Gigli et al. 2011).

The scope of this paper is to review the use of GBInSAR for slope monitoring. A summary of the most significant steps in the history of this technology is presented. Additionally, the current state of the art of GBInSAR and its application in recent case studies are described. A comparison of GBInSAR with other slope monitoring techniques for measurement of surface movements, including conventional systems such as robotic total stations, extensometers, global navigation satellite system (GNSS) and systems based on real-aperture radar (RAR), is also presented.

2. Historical review of GBInSAR for slope monitoring and present applications

The basic idea of GBInSAR for slope monitoring was derived from satellite technology. Since the 1990s, with the launch of ERS-1 (1991), JERS-1 (1992), RADARSAT-1 and ERS-2 (1995), satellite-based SAR has been able to exploit the phase information in radar images to detect ground displacements (Borgeaud et al. 1994; Srivastava et al. 1996). These developments of satellite technology had an early follow-up in analogue ground-based radar systems in the late 1990s.

In the year 2000, various authors (Pieraccini et al. 2000a, b; Tarchi et al. 2000) established the principles of ground-based interferometry for monitoring buildings and for terrain mapping. Finally, in 2003, in-field application of the technique was demonstrated for remote detection of slope movements (Tarchi et al. 2003; Pieraccini et al. 2003). In those early days, GBInSAR systems were based on laboratory equipment (i.e. vector network analysers) adapted for in-field use.

This remained the standard until the first design of a custom radar (Pieraccini et al. 2004), which was later developed and placed on the market (in 2007) by IDS SpA. More traditional radars using real-aperture antennas were already being used for monitoring mine slope stability (Reeves et al. 2000). Currently, RAR and synthetic-aperture radar (SAR) are both popular instruments for displacement monitoring of natural and engineered slopes.

It is worth noting that IBIS (Bozzano et al. 2011; Farina et al. 2011, 2013) from IDS and LisaLab (Antonello et al. 2008) from Ellegi are radars for slope monitoring based on the synthetic-aperture technique, while SSR from GroundProbe (Reeves et al. 2000), MSR from Reutech and the Gamma portable remote interferometer (GPRI) from Gamma Remote Sensing (Werner et al. 2012) are radar systems based on physical-aperture antennas.

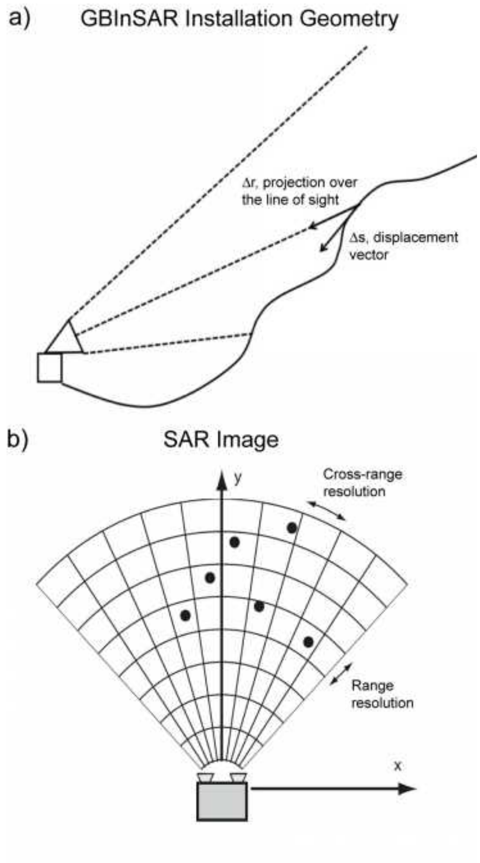

Figure 1. Ground based radar installation for slope monitoring (a) and SAR image characteristics (b).

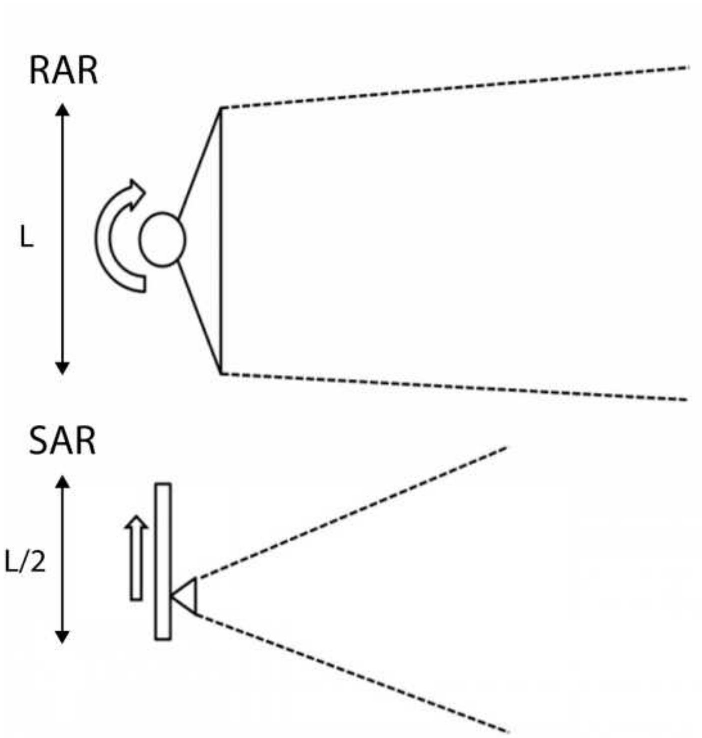

Figure 2. Real beam antenna (RAR) and synthetic aperture (SAR).

3. State of the art of the technology

A ground-based interferometric radar can remotely monitor landslides and open pit mines, provided it is installed in a position where a suitable view of the unstable area is possible (Fig. 1). Generally, a radar is able to detect the distance (range resolution) and the direction (cross-range resolution) of a target by transmitting and receiving electromagnetic waves.

The distance is obtained by evaluating the time of flight of backscattered electromagnetic waves. The direction of the target is obtained using a real beam or a synthetic aperture. In the first case, a large, high-gain (i.e. highly directional) antenna is rotated to scan all directions. In the second case, a small, low-gain antenna is moved along a guide in order to synthesise a larger antenna (Fig. 2). A remarkable feature of the latter solution is that the directivity performance of a physical antenna with dimension L can be simulated by scanning a dimension L/2. In other words, the scanner used for synthesizing the antenna is half the size of a real-beam antenna (Soumekh 1999). This means that SAR performance is improved by a factor of two in terms of angular resolution, all other features being equal (bandwidth, wavelength, range distance of the target).

The high spatial resolution of SAR may result in increased capability to detect localised slope movements (if used at the same working distance as a real-beam radar) or in an extension of the operating distance of the radar. On the other hand, a rotating antenna can scan 360°, while an antenna along a linear guide has a view that theoretically could be 180°, but in practice is about 90°, given that a physical antenna has a beam that cannot cover 180°.

In principle, the linear guide of a SAR or the small moving antenna could be rotated as a physical antenna, but this is rarely done (Noferini et al. 2009). In fact, experience shows that such a feature is not a real advantage for typical slope monitoring applications, for either shallow landslides or steep slopes.

It is worth noting that, when dealing with ground displacement measurements, the field of view should always be coupled with the line of sight (l.o.s.) concept. Since a radar purely measures the component of the 3D displacement vector along its l.o.s., the sensitivity of the radar to movement depends on how parallel its l.o.s. is to the 3D displacement direction. In this regard, the 360° scan capabilities of real-beam radar would be an advantage only when monitoring slopes on opposing natural valley flanks simultaneously (not a very common application) or scenarios with circular-shape slope geometries, as in open pit mines, but with the radar unit installed in the middle of the scenario (i.e. not a very favourable installation for mining operations). Both RAR and SAR provide two-dimensional resolution. RARs based on dish antennas exploit the narrow beam of the antenna to provide azimuthal and elevation angular resolution. A few RARs (e.g. the GPRI) are based on different types of antennas, offering range resolution capabilities to provide azimuthal and range resolution. SAR coupled with the range resolution capabilities of the radar also provides azimuthal and range resolution.

To present the user with a 3D visualisation of radar results (be it RAR or SAR), the most effective approach is to project the 2D radar images onto a 3D model [i.e. a digital elevation model (DEM)] of the monitored area. A DEM can be obtained from laser scanning, or also by using the same GBInSAR technique by performing two consecutive scans with a known baseline (Pieraccini et al. 2001; Noferini et al. 2007).

All interferometric radars detect the ground movement Dr by exploiting the differential phase information Du of the radar signal on the basis of the following relationship:

$$\Delta r = \frac{\lambda}{4\pi}\Delta\varphi$$

with λ wavelength. As the electromagnetic phase can be measured with high accuracy, using a wavelength on the order of a few centimetres, it is theoretically possible to detect displacements much smaller than a fraction of a millimetre.

However, other factors limit the performance of such equipment:

1. Atmospheric effects (Luzi et al. 2004): Humidity, temperature, pressure and turbulence change the refractive index of the atmosphere and, therefore, the path of the electromagnetic waves. The cumulative effect along the l.o.s. is an apparent displacement that has to be compensated using appropriate compensation algorithms that exploit the interferometric phases of highly coherent points, called permanent scatterers (PSs) (Ferretti et al. 2000; Noferini et al. 2005, 2008). This is a critical point, as the in-field capability of the GBInSAR technique to detect small displacements depends mainly on the effectiveness of these compensation algorithms to mitigate atmospheric effects.
2. Target decorrelation (Bernardini et al. 2008): A single pixel of the radar image is not a single target, but rather a collection of several reflecting objects whose movement is not necessarily quite correlated. This gives a phase contribution that can overlap with the phase shift related to the ground displacement to be detected. This is another critical point, and its solution also relies on sophisticated algorithms that can evaluate the effective decorrelation for each pixel and mitigate it by using the time series and the phase values of neighbouring pixels (Ferretti et al. 2000; Noferini et al. 2005, 2008).

4. Comparison of GBInSAR with alternative slope monitoring technologies

A wide range of sensors, based on different technologies, are used at present, in most cases in combination, for continuous monitoring of surface movements of natural and engineered slopes. The most common sensors for surface monitoring are robotic total stations, GNSS receivers, bar or wire extensometers and (albeit with some limitations on the accuracy achievable) terrestrial laser scanners.

Compared with GNSS, robotic total stations or extensometers, slope monitoring radar is a fully remote sensing technology. It does not require artificial reflectors or devices to be installed on the slope surface and makes it possible to effectively monitor very hazardous areas, even where human access is not possible. Another important difference is the spatial extent of the information provided. Robotic total stations and other types of sensors provide pointwise data over a network of benchmarks, while the GBInSAR system gives a spatially continuous dataset. This characteristic means that it is not necessary to know a priori the critical portions of a slope prone to collapse, always providing the user with full visibility of the movements along the slope.

Moreover, the electromagnetic waves used by radar are less sensitive to atmospheric changes compared with the laser signals used by total stations and laser scanners, leading to much higher accuracy (on millimetric scale), especially when working at long distances from the slope. In these conditions, the accuracy of data acquired by a total station is degraded to centimetric order while laser scanner accuracy is typically on the order of several centimetres (Abellán et al. 2009; Barla et al. 2010a, 2011; Fiani and Siani 2005; Lingua et al. 2008; Monserrat and Crosetto 2008; Teza et al. 2007). The Beauregard landslide, located in the NW Italian Alps along the Valgrisenche Valley, provides a good practical example. This landslide is a deep-seated gravitational slope deformation (DSGSD) (Barla et al. 2006, 2010a; Barla 2009) and occurs in the Pre-Permian crystalline basement of the Ruitor Unit, which predominantly consists of garnet mica schists and albite-bearing paragneisses with abundant intercalation of metabasites. As shown in Fig. 3, the landslide impinges on a 70-Mm^3-capacity reservoir (today the volume of water impounded is less than 6 Mm^3) and a 132-m-high concrete arch-gravity dam, with relevant implications in terms of civil protection and environmental issues.

The landslide deformation zone is identified by morpho-tectonic features such as trenches, scarps, counterscarps, niches, depressions, bulges and doubled ridges. It involves nearly the whole left slope of the valley, extending approximately 1,500 m in height from the reservoir (1,700 m a.s.l.) to the mountain ridge (3,200 m a.s.l.) and is 2.3 km long and 1.9 km wide at the slope toe.

Since the construction of the dam, an extensive monitoring network, including plumb lines, piezometers, topographic and total station targets and GPS monuments, has been installed. This was limited to the slope toe, close to the reservoir, with no data provided for the upper portion of the landslide (above 2,200 m a.s.l.), which is very difficult to access due to the rough terrain morphology and the substantial absence of paths. In these areas, conventional instrumentation would be nearly impossible to install, whereas the GBInSAR system is able to recover velocity and displacement data with spatial continuity.

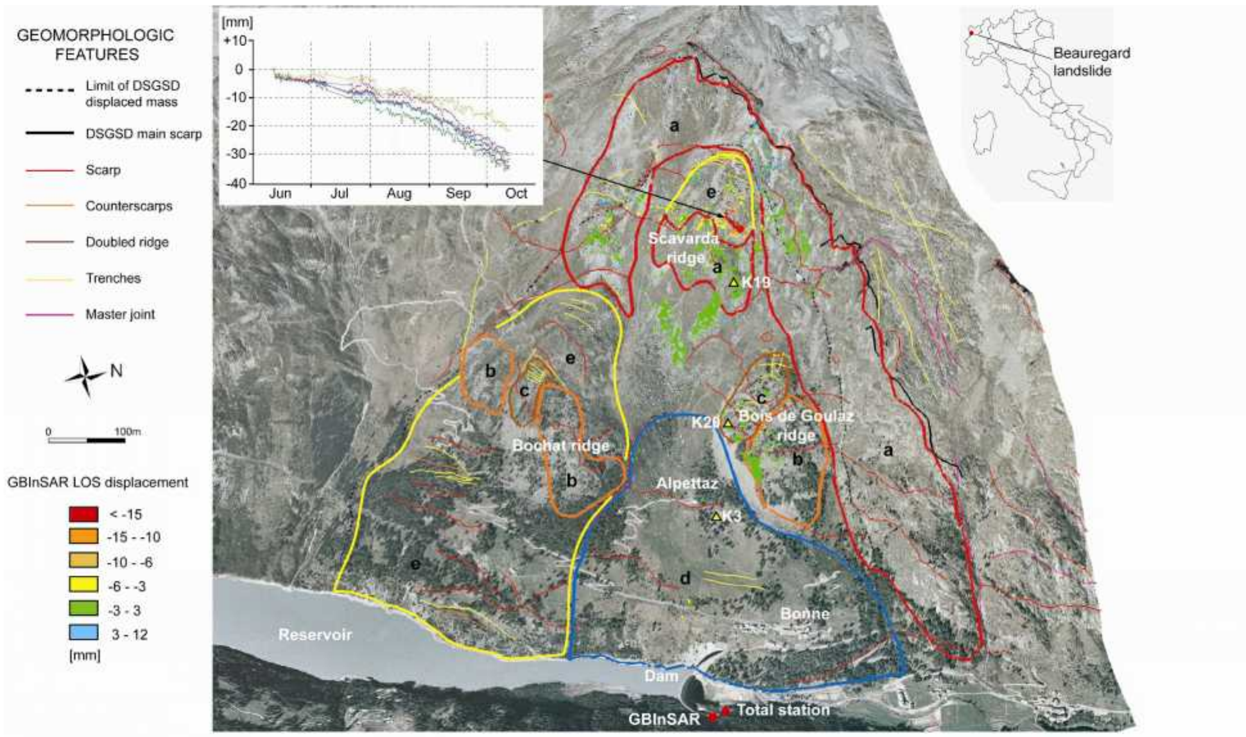

Figure 3. Beauregard landslide: results of the 2009 GBInSAR survey and geomorphologic features with indication of the main kinematic landslide elements : a) rock fall, b) block toppling, c) flexural toppling, d) slide on rotational surface, e) slide on compound surface.

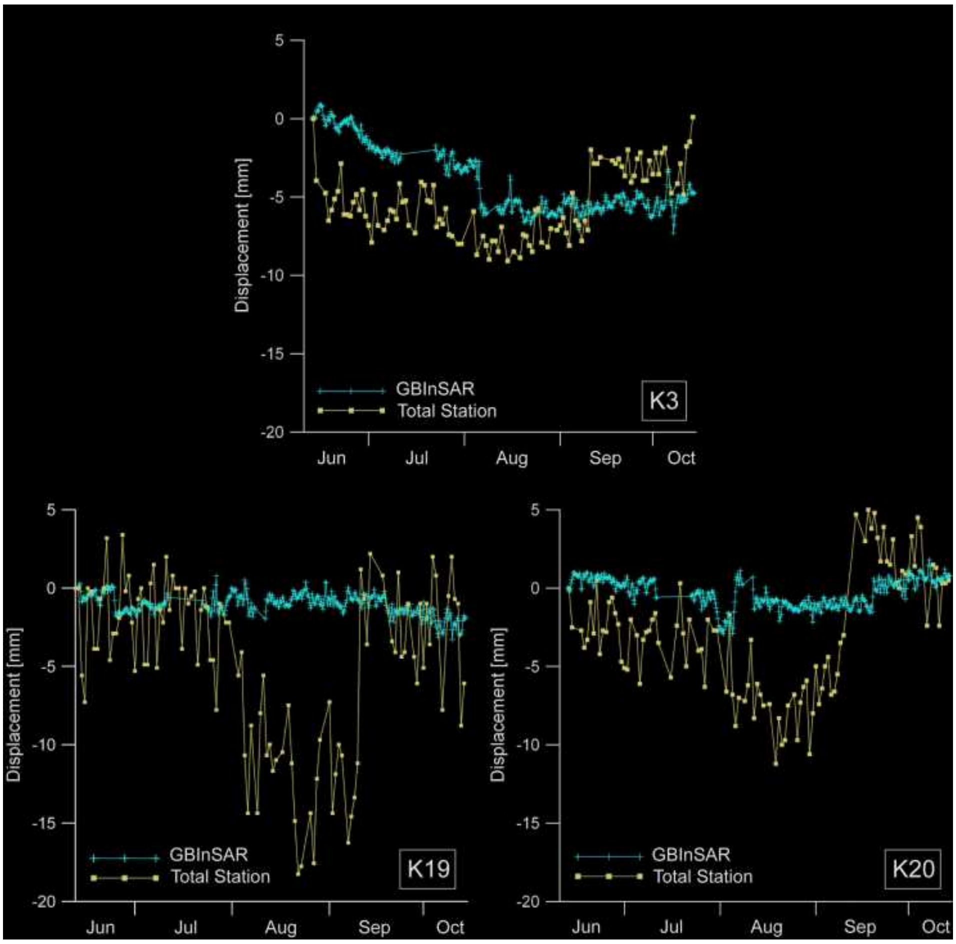

Figure 4. Comparison between the displacement measured from June 12th to October 14th 2009 by the GBInSAR system and total station on three points on the Beauregard landslide. The location of the points is shown in Figure 3.

In 2008 and 2009, two monitoring campaigns were carried out using the IBIS-L GBInSAR system (Barla et al. 2010a, 2011). The system was installed on a concrete platform at elevation of 1,770 m a.s.l., on the right dam abutment (Fig. 3). This location ensured a frontal view of the landslide, with the Bois de Goulaz and Scavarda Ridges being well monitored, at a distance of more than 1.0 and 2.2 km from the radar installation point, respectively.

Each monitoring campaign lasted 4 months (between June and October), with acquisition frequency of 20 min for a total number of more than 8,000 SAR images acquired. The images were subsequently processed by means of a specific algorithm that uses statistical analyses to select a grid of high-quality pixels (i.e. persistent scatterers). Atmospheric artefacts were removed from the interferometric signal based on a procedure derived from the PSs approach adapted to process GBInSAR data (Mariotti et al. 2012), and the corrected interferograms were finally converted into displacement measurements. The cumulated l.o.s. displacement detected during the 2008 campaign is shown in Fig. 3, which also illustrates the landslide boundaries and its main geomorphologic features.

The data obtained through the GBInSAR monitoring were of paramount importance to improve the understanding of the landslide mechanism and to develop a new geological–geotechnical landslide model. Different kinematic patterns along the Beauregard landslide were recognised, and new areas undergoing previously unknown movements, such as the Scavarda Ridge and the Bois de Goulaz Ridge, were revealed.

An elongated sector in motion on the Scavarda Ridge (between 2,300 and 2,500 m a.s.l.) was also clearly observed, with cumulated displacements of -45 mm during the monitoring interval. Negative displacements indicate a decrease of the sensor–target distance. The displacement pattern in this area is mainly due to rock falls, block and flexural toppling, and sliding, which result in debris that accumulates in two taluses in the middle land- slide sector. The time series of some selected pixels along the Scavarda Ridge are also shown in Fig. 3.

The slope sector between the Alpettaz and Bois de Goulaz Ridge is characterised by cumulative displacements of up to -15 mm. The area is bounded uphill by a set of minor scarps similar to the Scavarda Ridge, while a large talus is present in its frontal sector. For the lower part of the slope, between 1,800 and 2,100 m a.s.l., backscattering echoes due to isolated rock blocks and rock mass outcrops are also observed with displacements between -3 and -11 mm.

The occurrence of a non-homogeneous surface displacement pattern across the Beauregard landslide, with larger displacements (35–40 mm/year) for the upper slope (Scavarda ridge) and small and steady displacements (>10 mm/year) at the landslide toe, suggests two sectors with different behaviour (Barla et al. 2006, 2010a, b; Kalenchuk et al. 2010). Morphological structures such as faults, open cracks and trenches, widespread on the upper slope sectors, are clearly undergoing brittle deformation, while the toe portion of the landslide exhibits creep behaviour causing ductile deformation with development of slope bulging, depressions and counterscarps. The creep is controlled by the mechanical properties of a basal sliding plane associated with a thick cataclastic rock zone locally reduced to soil-like material (silt and clay), as recognised through deep borehole drillings and seismic surveys (Barla et al. 2011).

The higher accuracy of the GBInSAR data at long distances is well demonstrated in Fig. 4, where the GBInSAR monitoring data are compared with the displacements measured by a robotised total station at three points on the landslide (K3, K19 and K20). The displacement vector given by the total station is projected along the l.o.s. of the GBInSAR by applying a simple geometric correction.

The accuracy of the optical measurements is consistently lower than that of the GBInSAR (cm versus mm) due to their sensitivity to atmospheric variations of temperature, humidity and pressure. This is particularly evident for targets K19 and K20, located 1.1 and 1.7 km, respectively, away from the total station. A further significant aspect that can cause accuracy degradation for the total station measurements is the diurnal-nocturnal variation of temperature that can directly affect the optical targets.

Another important advantage of radar over conventional monitoring sensors is fast acquisition time. Compared with a robotic total station, which may need tens of minutes to complete a full cycle over a typical number of prisms, a radar image can be acquired in a few minutes, covering a very large area. This feature makes it possible to use a GBInSAR as a near-real-time monitoring system for early warning. Similar acquisition frequencies can be achieved using wire extensometers and GNSS with permanently installed receivers, albeit reducing the measurement to only a limited number of points.

On the other hand, since radar can only measure the component of the displacement along its l.o.s., integration of conventional sensors, mainly robotic total stations, with radar data is a common and beneficial practice in long-term monitoring of large slopes.

The main differences between SAR and RAR lie in how the slope is illuminated and the resolution achieved under different scenarios and geometrical conditions. The ground resolution cell of a GBInSAR system is typically much smaller than the cell of a RAR, for either gentle or steep slopes, thanks to the combination of the higher angular resolution with the range resolution provided by the bandwidth. For this reason, GBInSAR can be used effectively at longer ranges than RAR; for instance, a GBInSAR system working in the Ku band with 300 MHz bandwidth and an aperture of 2 m, at 2 km from a slope, has a resolution cell of 0.5 m by 8.6 m, compared with a cell of 17.6 by 17.6 m for a RAR with a 1.8-m dish antenna working in the X band.

Another significant difference between these two radar technologies is how they scan the monitored scenario. RAR operates by scanning the area of interest line by line, while SAR acquires the whole scenario in a single pass by moving along a horizontal guide. This architecture makes it possible for SAR to operate much faster, with a typical scan time of modern commercial sensors of about 2 min for a full-resolution image at 2.5 km distance, compared with 15–30 min for a modern real-beam radar scanning the same area extent.

Short scan time is mandatory for early warning purposes in order to increase the maximum measurable velocity (due to reduced phase ambiguity), enhancing the sensitivity to detect slope failure, and to reduce the impact of atmospheric effects on the acquired data. The scan time of RAR can also be reduced, but only by reducing the area coverage.

SAR is also less affected by strong signals backscattered from machinery passing through the illuminated area thanks to its acquisition mode that involves transmission and reception of radar signals over the whole monitored area, hundreds of times, during a single scan. Such an acquisition mode makes it possible to increase the overall signal-to-noise ratio and reduce the impact of strong moving reflectors on the pixel backscattered signal.

Figure 5 shows a displacement map obtained during GBInSAR monitoring of a 120-m-high rock slope in a limestone quarry in northern Italy (Barla et al. 2013). Despite the continuous passage of machinery through the radar-illuminated area due to mining activities, the SAR images did not suffer from any particular decrease of the signal-to-noise ratio with time.

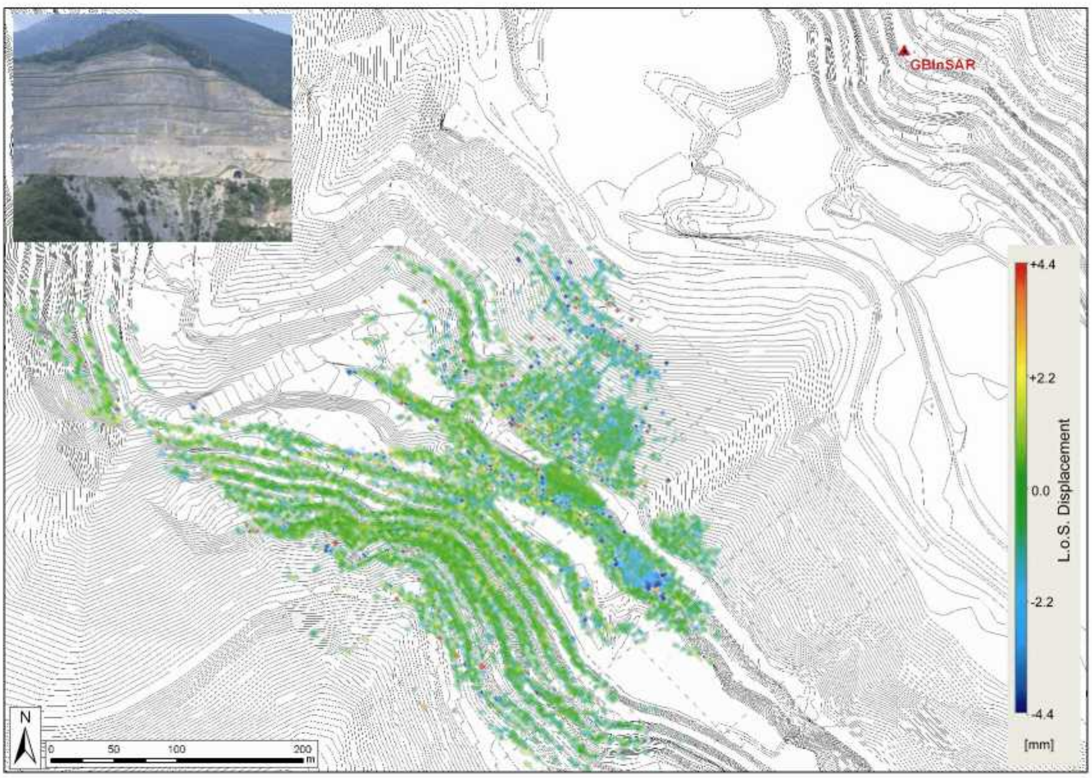

Figure 5. L.o.s. displacement map of a quarry rock face in NW Italy recorded from June 28th to July 7th 2011. The box shows a picture of the site.

In the example of Fig. 5, the rock slope is characterised by the presence of a 340,000 m^3 estimated rock volume standing in limit equilibrium conditions. The IBIS-L GBInSAR was installed on a stable area, at a distance of 500 m from the quarry face, to monitor in near-real-time the behaviour of the quarry face.

Due to the absence of a power supply network, a typical issue in quarries as well as during emergency conditions, the radar system was powered by photovoltaic modules for the whole length of the survey (3.5 months). The acquisition interval of the radar images was first set to 30 min with the possibility to increase the acquisition frequency up to 6 min in case of detection of anomalous slope behaviour.

More than 15,000 pixels, appropriate for displacement measurements, were obtained for the monitored scenario. Figure 5 shows the very good reflection that characterises exposed rock faces and the spatial continuity of the data, making the GBInSAR a perfect system for monitoring large rock quarry areas.

Figure 6 shows another example of a monitored open- pit quarry (the sandstone ‘pietra serena’ quarry in Firenzuola, Italy). In this specific case, the radar head was equipped with an azimuthal rotation system in order to enlarge the view angle. Different SAR images at different angles could be acquired and combined in post-processing to obtain a very large monitored zone.

Figure 6. GBInSAR installation at the sandstone (‘pietra serena’) quarry in Firenzuola (Firenze - Italy)

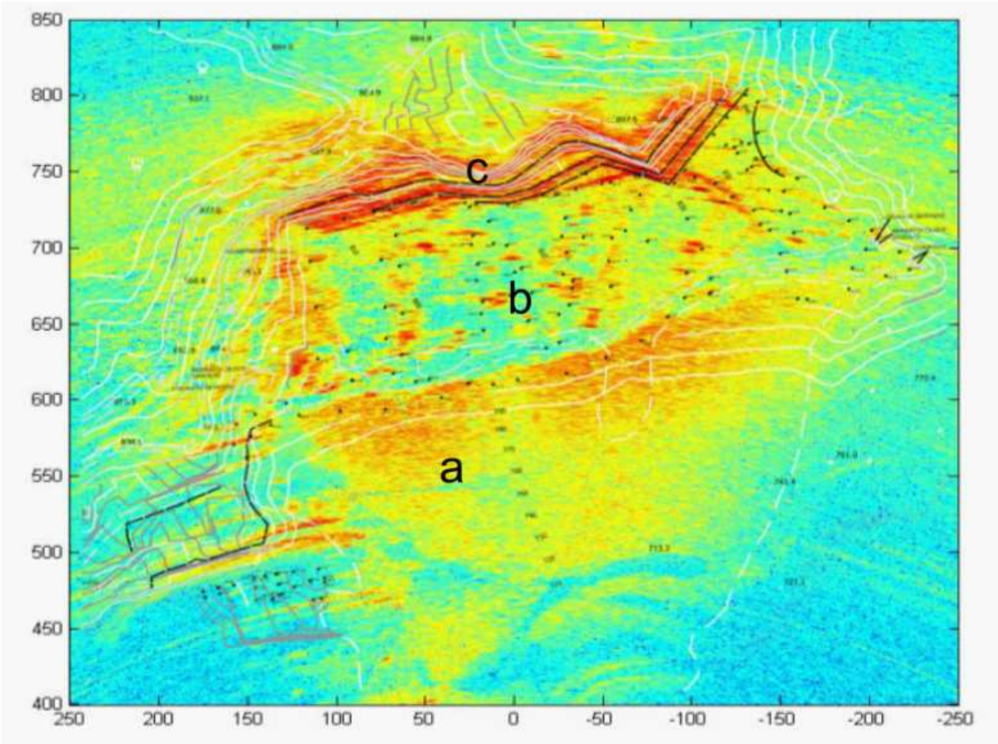

Figure 7. RCS radar image of the quarry in Firenzuola (Firenze - Italy)

The radar operated for 40 days from 16 February to 25 March 2009. The radar was installed on a hill in front of the quarry area, at a distance of 800 m. As no power supply network was available at the site, solar panels and wind turbines were installed in order to generate the energy for the system.

A radar cross-section (RCS) SAR image of the quarry is shown in Fig. 7, superimposed on a map of the same area. The origin of the local reference system is the radar location. This wide-angle map was generated from two sub- images acquired sequentially at two different angles. Three different zones can be distinguished: (a) the talus resulting from quarrying operations, between 450 and 600 m in range, (b) the quarry pit, between 600 and 700 m in range and (c) the main quarry face, between 700 and 800 m in range. Despite the continuous mining activities in zone (a), the radar images were not overly affected by noise and allowed the stability of the quarry face to be confirmed during the 40 days covered by the measurements.

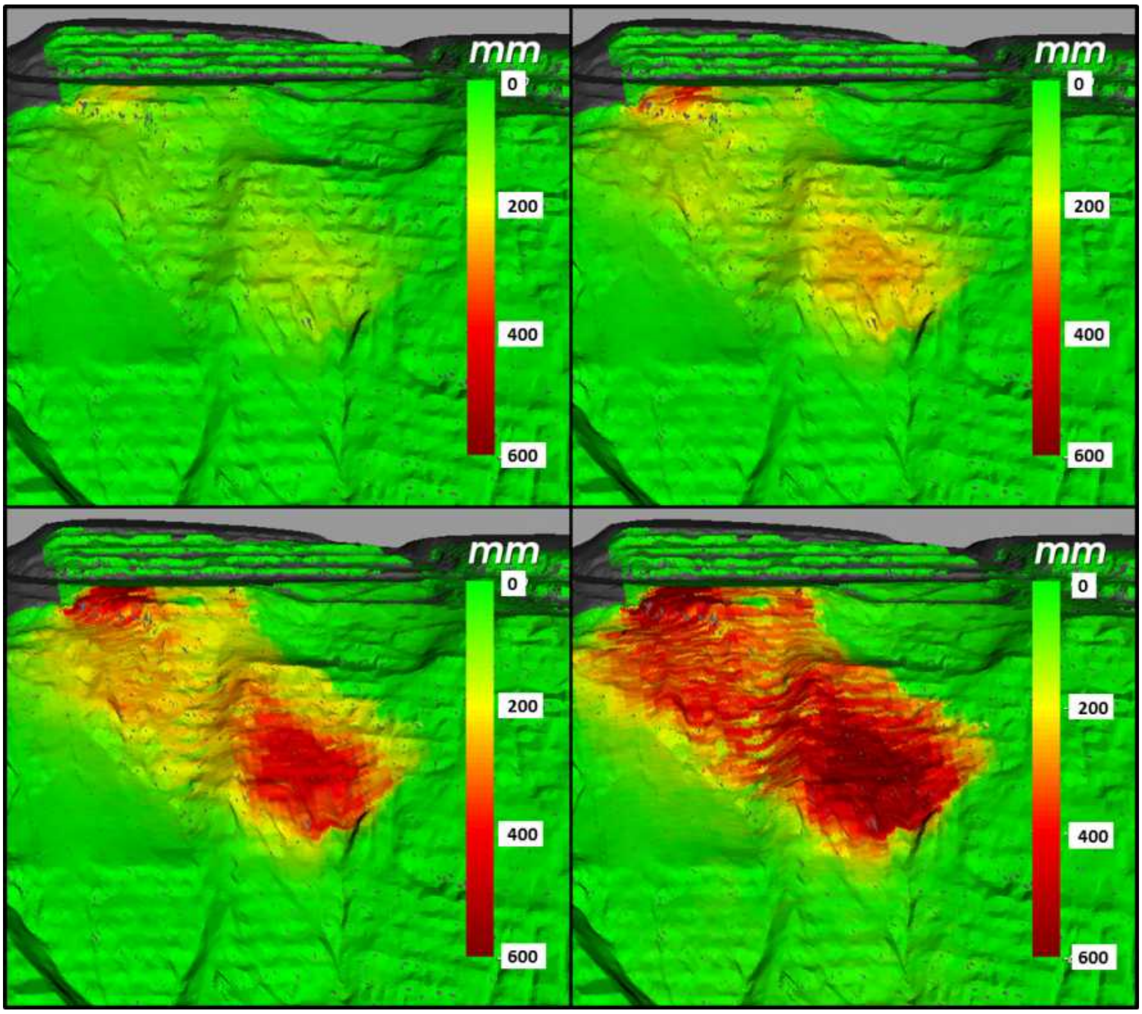

Figure 8. Evolution of cumulative displacement map of the moving area relative to the first week of November 2012

The importance of the short scan time of GBInSAR is emphasised by a significant application in an open-pit mine in North America, where the radar provided the information needed to manage potential failure during mine operations. An important mining face, excavated nearly a decade ago, had been monitored using traditional methods (total stations, extensometers, visual survey). As field access to install additional equipment had deteriorated over time, only limited monitoring data were available. Therefore, an IBIS-M GBInSAR unit was installed to monitor this old mine slope from a distance of 2,500 m. Information collected by the radar unit allowed clear identification of the extent of an unstable area (Fig. 8) and implementation of risk-mitigation procedures.

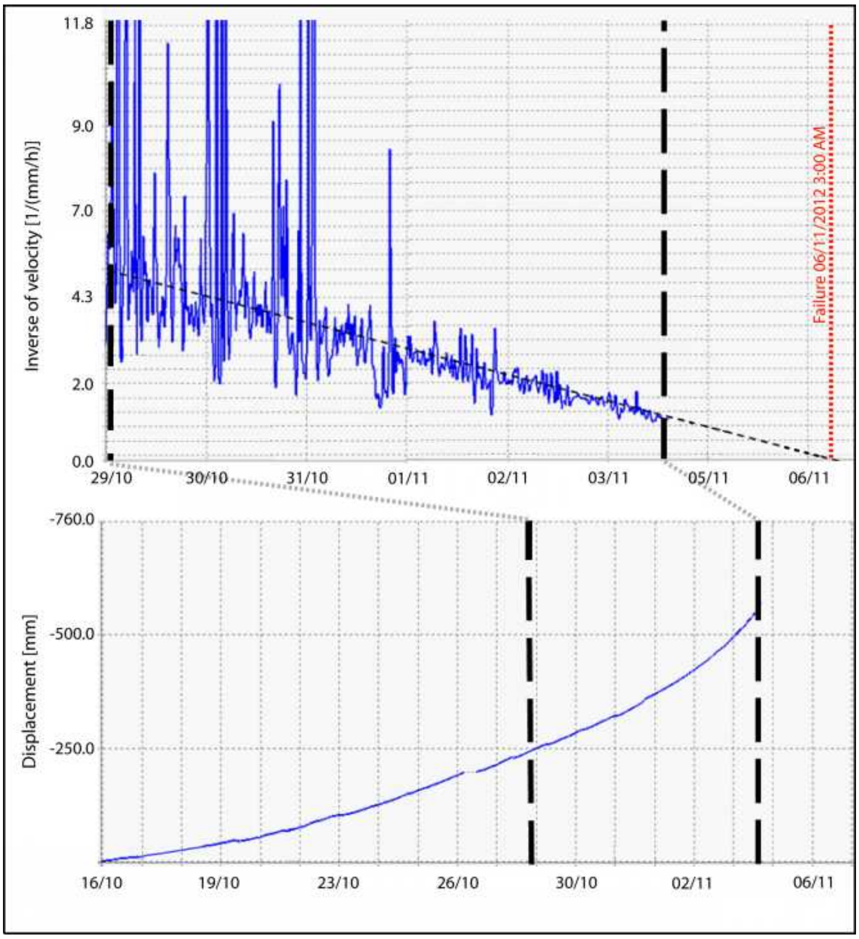

Figure 9. Displacement and inverse velocity time series of the moving area highlighted in Figure 8 over a time window from October to November 2012.

The ‘inverse velocity’ method (Saito 1969; Voight 1988; Fukuzono 1990) was used as an effective tool to track changes in the moving area, as it progressively accelerated (Fig. 9), and to predict the date of the expected failure. In the days prior to the expected collapse, the personnel were informed of the potential risks. During the afternoon before the event, the hazardous areas were closed to activities. The cumulative displacement trend showed a progressive increment until about 11 p.m. on 5 November 2012, when the monitored velocity exceeded the radar ambiguity threshold (60 mm/h in the current configuration). The actual movement continued to accelerate until failure, which occurred at 3:00 a.m. on 6 November. The collapse did not cause any damage to machinery or personnel, who were aware of the event.

This successful example demonstrates the capabilities of GBInSAR technology to manage the risks related to slope instability in open pit mines, by collecting information at a long range, tracking velocities and accelerations of the slope before a potential failure event.

5. Conclusions

This paper presents a review of the use of GBInSAR for slope monitoring. Starting from a summary of the most significant steps in the history of this technology and then focussing on the current GBInSAR state of the art, the paper compares GBInSAR with other slope monitoring techniques for measurement of surface displacements. A summary of the main technical features of the different SAR technologies and the other monitoring systems discussed is given in Table 1.

Table 1. Main characteristics of the monitoring techniques discussed.

	Accuracy	Temporal resolution	Spatial resolution	Range	Density of information
GBInSAR	≤ mm	< 3 min regardless of coverage	Continuous map, tens of thousands of pixels	≤ 4 km	High
RAR	≤ mm	From 5 to 30 min depending on converage	Continuous map, thousands of pixels	≤ 2.5 km	High to medium
Laser Scanner	≤ cm	Minutes to hours depending on coverage	Continuous map, millions of points	≤ 3 km	Very high
Robotized Total Station	mm	Tens of minutes	Pointwise	≤ 1 km	Pointwise
D-GNSS	≤ cm	Minutes	Pointwise	Tens of km	Pointwise

The presented examples clearly show how GBInSAR is effectively used today for slope monitoring, providing accurate measurements over large areas, without the need to install contact sensors, in almost all weather conditions and in near-real-time. These features, unique in the slope monitoring domain, allow the use of this technology for early warning monitoring of natural and engineered slopes, in cases of progressive movements potentially leading to a collapse. At the same time, the above-mentioned characteristics make GBInSAR ideal for long-term monitoring of slow landslides, improving understanding of slope failure mechanisms.

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