

REMOTE MONITORING OF A LANDSLIDE USING AN INTEGRATION OF GB-INSAR AND LIDAR TECHNIQUES

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ABSTRACT:

Landslide monitoring activities are of paramount importance for landslide hazard and risk assessment. They allow predictions to be made of the phenomenon evolution which can be used to define risk scenarios, especially when urban areas and infrastructures are involved. Over the last decades, spaceborne and, more recently, ground-based interferometric synthetic aperture radar (GB-InSAR) have been successfully used to identify and classify landslides. Ground-based synthetic aperture radar (GB-SAR) interferometry has already been recognized as a powerful tool, that can be considered complementary or alternative to spaceborne SAR interferometry for terrain monitoring and to detect structural changes in buildings.

Terrestrial laser scanning (TLS) is a technique increasingly used in remote sensing of unstable slopes. Detailed digital models of the observed surface are generated with centimetric resolution. In particular, if multitemporal scans of the same area are performed, these scans can be compared in order to obtain displacement fields.

Both GB-SAR and TLS observations were planned at the end of July 2007 and at the end of October 2007 in order to assess the hazard of a quarry that is subject to ground instabilities (the Ex-Locatelli quarry near the Baveno village in the Italian Alps on Lake Maggiore). This paper reports on these measurement campaigns and on a test site set up in Florence (Italy) and discusses the advantages of the combined use of these innovative techniques. The availability of radar and laser data at the same time has allowed a comparison to be made of the two techniques and has provided an effective validation test for both.

1. CASE STUDY: THE EX-LOCATELLI QUARRY LANDSLIDE

The Ex-Locatelli quarry is located near the Baveno village in the Italian Alps on Lake Maggiore. Its mining activities have currently been suspended because of many ground instabilities that occurred in the past. The main instabilities occurred during intense and long precipitations and were characterised by debris flows and rock-falls. Because of these instabilities the landslide crown withdrew by about 160 m between 1996 and 2005. The rocky landslide can be considered quiescent but there is a risk of reactivation (Fig. 1).



Figure 1. The landslide in the Ex-Locatelli quarry

The fractured area extends from an elevation of 735 m a.s.l. at the crown down to 525 m a.s.l. at the toe. Its total length is approximately 280-300 m and its maximum width is about 70 m.

The area is characterised by complex geological and structural features (Crosta *et al*, 2007).

The Verbano Cusio Ossola Province Authorities decided to monitor the area to understand the entity of movements and their spatial distribution. This can easily be done using GB-InSAR and TLS measurements.

2. MEASUREMENT CAMPAIGN

2.1 GB-SAR measurements

The employed ground-based radar instrumentation consists of a CW-SF (continuous-wave step-frequency) transceiver unit (Vector Network Analyzer HP 8753D) working at C-band, a linear horizontal rail of about 2 m where the antennas move to scan the synthetic aperture, and a personal computer to control the VNA, the motion of the antennas, the data recording and all the other operations necessary to carry out the measurement session. The employed ground-based radar instrumentation was designed and realized by the Department of Electronics and Telecommunications at the University of Florence, with the support of IDS-Ingegneria dei Sistemi SpA Pisa.

The radar instrumentation was installed at an elevation of 338 m a.s.l., on a suitably built platform made on a stable concrete building belonging to the Municipality of Baveno, to ensure good visibility of the landslide (Fig. 2). The medium distance between the GB-SAR instrument and the landslide was about 600 m.



Figure 2. The GB-SAR installed on a building

The instrument was locked onto mechanical frames fixed to two concrete bases realized on the building (Fig. 3). Using these frames, it will be possible to put the radar back in the same position during the next measurement campaigns.

The GB-SAR monitoring was carried out over five days and 127 SAR images were acquired in three separate sequences.

During this campaign, it was also possible to obtain some radar images acquired from different heights (centimetric shifts) which were necessary to realize a DEM of the scenario (Atzeni *et al.*, 2001) in order to compare it with the one realized by laser scanning technique.



Figure 3. The GB-SAR instrument attached to mechanical frames fixed to two concrete bases realized on the building

The main radar parameters adopted during the measurement campaign are summarized in Table 1.

The acquired radar images exhibit a fixed spatial resolution of 3 m along the range direction and a variable cross-range spatial resolution that varies from 2.7 m at 200 m of distance from the radar, to 6.7 m at 500 m of distance and so on.

The SAR measurements were processed using a differential interferometric SAR technique based on the calculation of the phase difference (proportional to displacement) that occurs between two complex SAR images acquired at different times, containing amplitude and phase information of the received echoes from the scenario.

When the phase instability sources are negligible or corrected and in the case of measurements carried out without any modifications of the observation geometry (zero baseline geometry), the differential phase is related to the variation in the range that separates the centre of phase of each pixel from the radar system along the radar line of sight (Luzy *et al.*, 2006).

Polarisation	VV
Target distance	300-700 m
Transmitted Power	-3.0 dBm
Band	50 MHz
Central frequency	5.885 GHz
Number of transmitted frequencies	801
Linear scansion length	1.9 m
Linear scansion point number	191
Antenna gain	15 dB
Measurement time	35 min

Table 1. Main radar parameters used during the measurement campaign in Baveno (Italy)

The differential interferometric SAR technique was only applied to pixels that exhibit good coherence, that is higher than 0.9, where coherence stands for temporal stability of the radar signal reflected by the scenario. The temporal coherence map obtained with the acquired data is represented in Fig. 4 with a colorimetric scale.

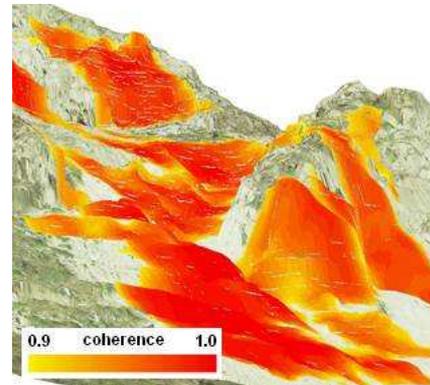


Figure 4. Temporal coherence map of pixels with coherence higher than 0.9

SAR image reconstruction was obtained by means of a recent DEM of the observed area and it was also aided through the use of an active radar calibrator, which consists of a movable radar marker that appears as a bright point in a radar intensity image, to support SAR image interpretation and georeferencing.

It was also possible to take into account the atmospheric effect by modelling it with a polynomial function whose coefficients were estimated considering two stable areas of the scenario (Noferini *et al.*, 2005).

Georeferencing of the SAR images

In order to correctly locate the acquired SAR images, it was necessary to determine the spatial transformation between the coordinate system of the GB-SAR instrument and the reference coordinate system of the DEM of the scenario (UTM-WGS84). The first is defined by the coordinate axes X_{SAR} , Y_{SAR} and Z_{SAR} , while the second one is defined by the coordinate axes X_{DEM} , Y_{DEM} and Z_{DEM} .

Since the GB-SAR instrument was installed horizontally, the Z_{SAR} axis can be considered coincident with the Z_{DEM} axis (the area extension was limited therefore this hypothesis can be accepted); hence there are three parameters of the spatial transformation between the two coordinate systems: a rotation parameter and two translation parameters. At least two points

known in the two coordinate systems are necessary to estimate the three parameter values.

A particular procedure was performed between the first and the second sequences of the acquired radar images to determine the coordinates of three reference points in the two coordinate systems. Three SAR images were acquired, each of which was related to one of the three positions (CR1, CR2, CR3) assumed by an active radar calibrator in the monitored scenario (Figure 5).



Figure 5. Active radar calibrator (left) and the CR1, CR2, CR3 positions in which it has been installed (right) in order to correctly locate the acquired SAR images

The active radar calibrator appears as a bright point in the radar intensity images, therefore it was possible to easily determine the coordinates of the positions assumed by the calibrator in the SAR coordinate system. The coordinates of these positions have instead been determined in the DEM coordinate system through topographic measurements.

Thanks to the estimation (least square method) of the three parameter values, it was possible to calculate the coordinates, in the DEM coordinate system, of the positions assumed by the two antennas of the SAR instrument along its rail and to correctly apply the focusing SAR algorithm, in this way obtaining radar images in which the position of each pixel is known in the DEM coordinate system.

Estimation of the measurement precision

An estimation of the radar measurement precision was performed. There is also an error on the pixels which have a higher coherence than the lower limit value (0.9 in this case) that has to be estimated to determine the measurements precision.

The method adopted in this case considers the distribution of the phase difference values of the interferograms concerning two stable areas of the scenario (Fig. 6 left).

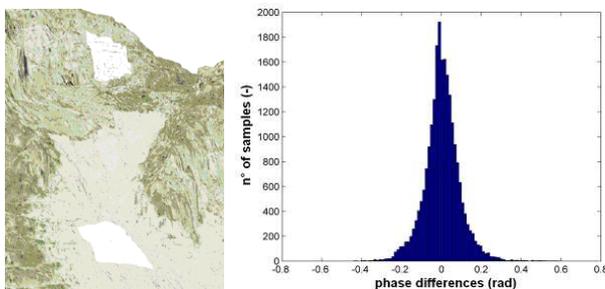


Figure 6. Representation of the two stable areas used to estimate the radar measurement precision (left) and distribution of the phase difference values of the interferograms (right)

An histogram of this distribution is represented in Fig. 6 (right). The histogram is similar to a gaussian distribution, with a standard deviation (σ) of 0.35 mm. Hence, a measurement reliability from a statistical point of view (precision) of ± 0.70 mm at 95 % reliability has been obtained.

For the results of the GB-SAR campaign see section 2.4.

Test site in Florence

In order to estimate the accuracy of the GB-InSAR by means of known displacements a measurement campaign using a test site in Florence was performed before the measurement campaign in Baveno.

The GB-SAR was installed on a stable concrete platform in the University of Florence park. A particular device was installed at a distance of about 120 m from the radar, to generate controlled displacements. This device consists of an electric engine, a worm and a reflecting metal disk oriented in the direction of the radar (Figure 7).



Figure 7. Device employed to generate controlled displacements (Florence test site)

Thanks to this device, several displacements (varying from 0.05 mm to 5 mm) were imposed with a precision of 0.01 mm and they were measured with the GB-InSAR technique.

The main radar parameters adopted during the measurements are summarized in Table 2.

Polarisation	VV
Target distance	120 m
Transmitted Power	-3.0 dBm
Band	300 MHz
Central frequency	5.650 GHz
Number of transmitted frequencies	801
Linear scansion length	1.9 m
Linear scansion point number	191
Antenna gain	15 dB
Measurement time	65 min

Table 2. Main radar parameters used during the measurements in the Florence test site

The minimum and the maximum standard deviations of the measurements were 0.03 mm and 0.19 mm respectively, while the RMS (root mean square) was 0.13 mm. These values are smaller than the precision value estimated in the Baveno campaign because a target was used in this test site which was optimal for the interferometric measurement because of its high reflectivity and correct direction with respect to the radar instrument.

2.2 TLS measurements

Terrestrial laser scanner measurements were performed during the GB-InSAR monitoring to obtain a precise and updated DEM of the landslide.

A Riegl LMS-Z420 laser scanner, which allows long range measurements (up to 700 m) and centimetric precision in the 2.5 cm range, was employed (Fig. 8).

The laser scanner was installed a few metres from the GB-SAR thus ensuring good visibility of the landslide and of the markers installed in the surrounding area. These markers are necessary to georeference the acquired data and their position was acquired through topographic measurements (see section 2.3).

The laser scanner data acquisition lasted about 40 minutes for each of the two scans necessary to describe the landslide and about 33 million points were acquired.

The global point cloud used to generate the 3D model of the landslide was obtained after filtering and registration of the two scans.



Figure 8. The Riegl LMS-Z420 Laser scanner

The laser scanner data were processed with a new SirIo software realized thanks to a collaboration between the SIR society (Italy) and the Geomatics Research Group of the Politecnico di Torino.

The laser scanner was firmly connected to a calibrated digital camera (the Nikon D1X camera). Many digital images of the scenario were acquired and they were employed to integrate the laser scanner data with their radiometric content.

Thanks to the SirIo software it was also possible to generate solid images of the landslide (Bornaz *et al.*, 2003), which allow direct measurements to be easily made on the point cloud, such as distances, angles, plane orientations,...

A portion of the processed laser scanner data is reported in Figure 9.



Figure 9. Portion of the processed laser scanner data

2.3 Topographic measurements

In order to correctly locate the radar and laser scanner data it was necessary to create a local coordinate system made up of three control points and many markers. The coordinates of the control points were estimated using relative-static GPS positioning, while the coordinates of the other points were acquired by the total station. This latter instrument was also employed to measure the positions assumed by the active radar calibrator that are necessary for the radar data georeferencing.

All the topographic measurements were adjusted with a commercial software, and centimetric accuracy was obtained in the estimation of the coordinates of the measured points.

2.4 Results of the campaign

The final SAR interferometry product consists of displacement maps of the scenario, which provide information about the distribution and entity of the movements.

The interferometric maps were obtained through a masking procedure that excludes areas with lower coherence than the reference lower limit value (0.9 in this case) and by focusing the radar images on a DEM of the scenario.

Three displacement maps – corresponding to the three sequences of acquired radar images - were obtained. One of them is reported in Figure 10.

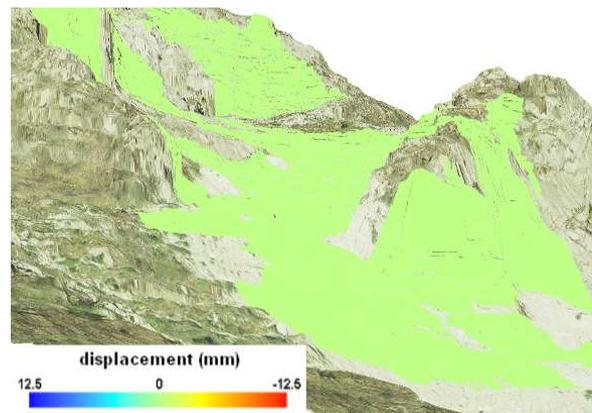


Figure 10. Displacement map relative to the first sequence of SAR images

No appreciable displacements are present in any of the maps as could be foreseen; the landslide is in fact quiescent but at risk of reactivation and no precipitations occurred during the monitoring campaign.

It will be possible to repeat the SAR measurement campaign four-six months after the first campaign in order to determine any displacements that have occurred during the time interval between the two campaigns. In this case, it will be necessary to adopt the “permanent scatterers” (or “coherent points”) technique (Ferretti *et al.*, 2001).

This technique is based on the selection of stable coherent radar image pixels – between successive campaigns - whose interferometric phases can be considered only affected by atmospheric variability and any spatial movements.

The final products of laser scanner measurements are 3D models and solid images of the scenario. In this case, we obtained a complete 3D model and four solid images of the landslide. Only on the upper part of the scenario laser data was the density not so good because of the long distances, which

were longer than the upper limit distance of the instrument (700 m).

A DEM was also obtained from radar images. A portion of this DEM is represented in Figure 11.

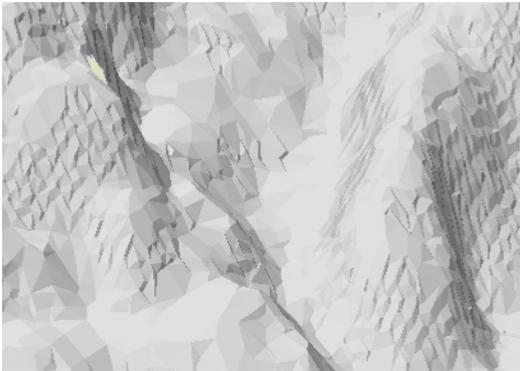


Figure 11. Portion of the DEM obtained from processing radar images

Since the DEM was generated with radar images, which have a cross-resolution that varies with distance, the DEM also has a resolution that decreases as the distance increases. The height accuracy is of about 5 m and is not comparable with the one of the laser scanner DEM, which has a centimetric accuracy.

3. COMPARISON BETWEEN THE TWO TECHNIQUES

Thanks to the measurement campaign, the processing of the acquired data and the comparison between the achieved results, some important aspects of the two techniques can be underlined.

3.1 GB-InSAR technique

The main negative and positive aspects are reported:

- only the displacement component parallel to the line of sight (LOS) of the radar can be detected; displacements in other directions cannot be measured. Hence, it is necessary to install the instrument in a useful position to monitor the displacement component of interest;
- the cross-range resolution of SAR images decreases with an increase of the measurement distance, and pixels with dimensions of some square metres are obtained at 200 m, but of more than 10 m² at 1 km of distance. This fact limits the application of the GB-SAR technique for the study of slope movements. Since radar data are obtained through spatial averaging on pixels which have an area of several square metres, the displacement measurements are only representative if they refer to instability phenomenon of large volumes or in which differential displacements in the landslide body are limited;
- it is possible to reduce the pixel dimensions of radar images by using, for example, higher frequencies of the radar signal than the ones employed in the case study (but the measurements are more influenced by atmospheric effects);
- a careful analysis of coherence behaviour of the scenario and of the limit values of pixel coherence is necessary in order to obtain good results from the interferometric process;
- the instrumentation is quite heavy and bulky (mainly because of the linear rail dimensions, which are usually greater than 2 m), therefore it is necessary to transport it with all-terrain vehicle or helicopter to the installation position;

- the instrument has to be installed on a stable base, which often needs to be specifically built;
- the GB-SAR instrument has to be installed in such a position that no metal objects (poles, panels, ...) are in a range of 10-20 m between the instrument and the scenario. If this condition is not respected, the radar images could in fact be saturated by the high reflectivity of metal objects nearby and they cannot be used for displacement monitoring. Motor vehicles passing between the instrument and the scenario could also create problems and interrupt the monitoring process. Furthermore, the presence of thick vegetation or stretches of water in the immediate proximity can create problems similar to the ones described concerning metal objects;
- the GB-InSAR technique can reach high accuracy in the measurement of displacements (as demonstrated in the Florence test site); movements of the order of a fraction of the wavelength, corresponding to sub-millimetric displacements per day, can be appreciated during continuous monitoring. Instead, on a long term time scale, i.e. a few centimetres per year, it is not possible to reach similar accuracy because of phase decorrelation. In these cases, it is necessary to turn to different techniques, such as the "coherent points" technique, with a decrease in accuracy; in these cases, the displacement measurements are limited to many sparse points and the broad information provided by the interferometric displacement maps obtained with continuous monitoring is, in this way, lost;
- this technique allows remote monitoring up to distances of 3-4 km, without requiring the access of human operators in the monitored area, thus reducing risks in the case of dangerous ground instabilities;
- the displacement measurements can be realized almost in real-time, with a minimum time for radar image acquisition of the order of tens of minutes;
- radar data acquisition can be carried out independently of the weather and lighting conditions, even though, in the case of heavy rain or snow, it would be better to stop the acquisition because of data deterioration;
- the displacement maps obtained through the interferometric process are easily and immediately interpretable (displacements are usually displayed with colorimetric scales) and they allow a global vision to be obtained of the monitored scenario, and it is therefore possible to identify and quantify the movement extension;
- this technique allows the generation of DEM of the monitored area with an accuracy of a few metres. This accuracy is not comparable with that provided by laser scanner techniques, but it is sometimes sufficient for interferometric displacement map focusing.

3.2 TLS technique

The main negative and positive aspects are reported:

- laser scanner acquisitions have to be carried out in good atmospheric conditions (no precipitation); in the case of acquisition of digital images, a good illumination of the scenario is also necessary;
- TLS technique can only reach the same measurement accuracy as the GB-SAR technique over small ranges (tens of metres), but it provides information on each acquired point and non averaged data on pixels of some square metres;
- laser scanners allow millions of points of the monitored scenario to be quickly acquired and provide a complete 3D model of the scenario;

- when the model of the monitored area has been generated, computations about volume variations as well as on the differences between the multitemporal models of the same object can be carried out. Since the model accuracy (in the case of environmental applications) is usually centimetric, only displacements greater than a few centimetres can be detected;
- laser scanners are usually lighter and less bulky than GB-SAR instrumentation and it is possible to transport them without particular vehicles;
- laser scanner techniques allow dense digital elevation models (DDEMs) of the observed object to be generated; in the case of multitemporal scans, it is possible to detect displacements in each small portion of the observed area and not in pixels of a few square metres of dimension as in GB-InSAR products;
- no problems occur in the case of a change in the laser scanner position between repeated measurement campaigns because the reference system of the models is "fixed" on the markers, while even millimetric changes in the position of GB-SAR instrumentation can dramatically reduce the measurement accuracy;
- the measurement range can vary to a great extent for different instruments; in general it can vary between 10 m up to some kilometres;
- thanks to the comparison between multitemporal scans, 3D displacements can be detected, while with GB-SAR only the displacement component parallel to the line of sight of the instrument can be detected.

4. CONCLUSIONS AND FUTURE WORK

In this work, both GB-InSAR and TLS measurements were used to monitor the landslide of the Ex-Locatelli quarry.

No displacements occurred during the five days of monitoring: the landslide is in fact quiescent but at risk of reactivation, and no precipitations occurred during the monitoring campaign. The local Authorities are at present considering a new campaign.

Thanks to this work, both techniques have been applied and their principal features have been compared.

The GB-InSAR technique can be useful for many applications, such as continuous or repeated monitoring of slopes, landslides, quarries, glaciers and of the snow cover (Achache *et al.*, 1996; Ferro-Famil *et al.*, 2005; Fortuny-Guasch *et al.*, 2005). It can also be applied to monitor buildings and large infrastructures, such as dams, bridges and towers, either in static or dynamic conditions. This technique can be very useful for the remote monitoring of terrain slopes and as an early-warning system to assess the risk of rapid landslides.

Its measurement accuracy has been estimated from a statistical point of view both in a test-site in Florence and during the monitoring campaign of the Baveno landslide. In the case of continuous monitoring, a sub-millimetric accuracy can be reached (± 0.70 mm at 95 % reliability in the case of study), while in the case of repeated monitoring it is not possible to reach a similar accuracy because of phase decorrelation. In this latter case, it is necessary to turn to different techniques, such as the "coherent points" technique, with a decrease in accuracy; in this case, the displacement measurements are limited to many sparse points and the broad information provided by interferometric displacement maps obtained with continuous monitoring is thus lost.

The TLS technique allows a complete and accurate DEM of the monitored area to be obtained. It can be useful for natural hazard and risk assessment where morphological investigation is a starting point to evaluate stability properties. In the case of

multitemporal scans, it is possible to compute volume variations of the observed object, providing 3D displacement measurements, while, with the GB-InSAR technique, only the displacement component parallel to the line of sight of the instrument can be detected.

These two techniques can be considered complementary. TLS can be usefully used to generate an accurate digital model on which SAR images can be focused. The data obtained by SAR could also be linked to the TLS measurements, but limited to some points in order to reconstruct the absolute phase information of the entire area observed by the radar.

It can be concluded that the integration of GB-InSAR and TLS techniques is a powerful remote sensing system for environment monitoring.

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