Monitoring geotechnical structures by ground based radar interferometry

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Abstract

This paper describes two novel remote sensing techniques based on radar sensors, respectively the Synthetic Aperture Radar (SAR) and the Real Aperture Radar (RAR), and some applications to relevant geotechnical problems with the aim to demonstrate the outcomes these types of sensors can provide. The case studies here described show how the SAR technique can provide useful information to interpret landslides' kinematics and how the RAR can be used to monitor dam displacements and tunnels' convergences.

1. Introduction

Measuring and monitoring displacements and deformations of geotechnical structures, such as natural and engineered slopes, quarries and mines, tunnels, dams and other civil infrastructures, is nowadays a key task for civil engineers and geologists. The precise and accurate assessment of these physical quantities can be used to monitor the expected behaviour of such structures during the construction stage (observational approach), to assess their performance or state of damage (for man-made objects), their possible interactions with further man-made structures as well as for early warning purposes.
The Ground-Based Interferometry based both on Synthetic Aperture Radar (GBInSAR) or on Real Aperture Radar (RAR) is an active microwave remote sensing system, designed in general terms to monitor the displacements of objects (Atzeni et al. 2015; Leva et al. 2003; Luzi et al. 2004; Mazzanti, 2012; Rudolf et al. 1999; Tarchi et al. 2003). In the last ten years, ground based radar interferometry has proven to be a powerful tool for monitoring displacements and deformation that accompany mass movements as landslides, glaciers, volcanic activity as well as the displacement and the deformations of structures and man-made objects (Antolini, 2014; Atzeni et al. 2015; Barla et al. 2010, 2011; Bartoli et al. 2008). These different application fields take advantage of the unique capabilities of SAR to measure displacement and velocity very quickly (with acquisition frequency of up to few minutes) over large areas with sub-millimeter accuracy and in almost any weather conditions without the need to install contact sensors on the slope. As a full remote sensing instrument, the radar interferometry does not have therefore the necessity of site accessibility to the monitored scene which in many case is highly hazardous. These particular features, not offered today by any alternative monitoring technologies (at least to the same extent), can be effectively adopted to support users in their decision-making processes (Atzeni et al. 2015). In addition, this technique is capable of collecting quantitative information on the behavior of natural or engineered slopes or man-made objects from either a spatial or a temporal point of view. It provides, over long periods of time, accurate geo-referenced outputs (i.e. displacement and velocity maps) and allows the users to integrate radar outputs into geotechnical and structural analysis of failure mechanisms. Another important characteristic of the GBInSAR technique lies in its capability to monitor real time or near real time the deformation of an observed scene. The meaning of near real time (NRT) is hence referred to the determination of the displacement field of the observed scene at each time step and after each acquisition with the least delay possible. This is a major advantage with respect

both to most of the conventional geotechnical in-situ instrumentation and to other remote sensing techniques, i.e. Terrestrial Laser Scanner (TLS), automatic topographic total station (ATS) and spaceborne SAR. The NRT evaluation of the displacement field of natural phenomena, damaged or threatened buildings and infrastructures can act as the basis for the implementation of early warning system and civil protection plans.
In this paper, after a brief description of the main principles of radar interferometry, the capability of SAR and RAR techniques are discussed on the basis of some experimental applications, in order to provide a comprehensive assessment of their main features for geotechnical structures monitoring.

2. Ground based radar interferometry

The images obtained by means of the GBInSAR, here called for the sake of simplicity SAR images, are two dimensional complex images where each pixel contains two main information of the radar signal, the amplitude (A) and phase (ϕ). The radiometric amplitude of each SAR image is directly related to the power of the back-scattered signal from all the objects contained in each resolution cell (represented as a pixel) and it is typically used to recognise the different reflecting objects in the SAR image. The phase of each pixel is instead related to the sensor-targets distances and it can be exploited to obtain the accurate position of each target. By comparing the variation over time of the pixel phase, it is thus possible to measure the displacements and the velocities of the different objects occurred between the two consecutive acquisitions.
The deformation measurements technique can be summarized in Figure 1 which illustrates the radar interferometry measurement principle.

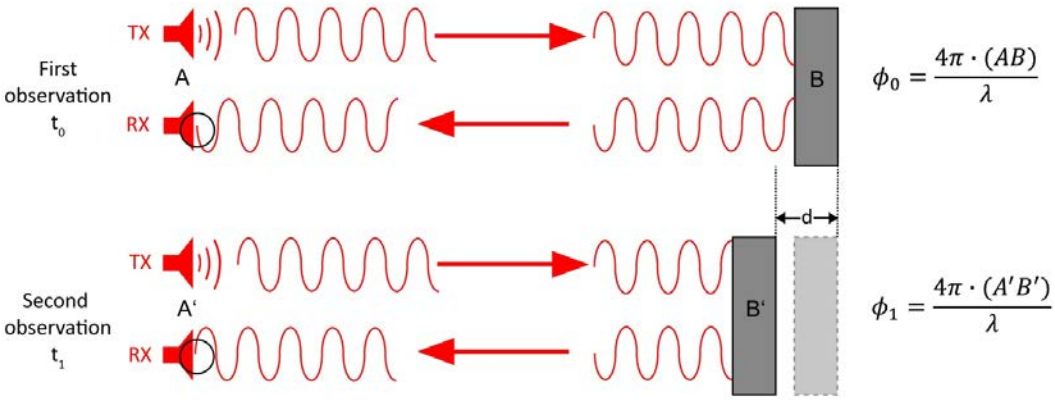
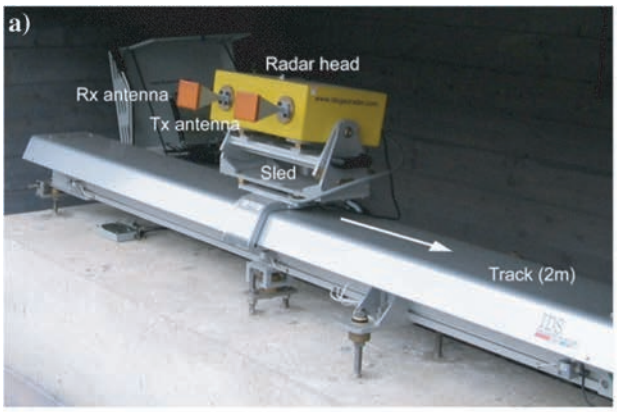


Figure 1. Working principle of radar interferometry for deformation measurement.

The sensor is installed on a stable terrain in front of a generic monitored area. During the first observation (t_0), a certain phase (ϕ_0) related to the sensor-target distance AB due to the reflection of the grey object is obtained. If the object suffers a displacement *d* between the two acquisitions and a second observation (t_1) of the same area is made, a different phase (ϕ_1) is retrieved. This quantity is related to the displacement *d* of the object occurred between the two observations. The displacement *d* can therefore be obtained by the following equation:

$$d = \Delta\phi_{(A'A)} * \frac{\lambda}{4\pi} \tag{1}$$

where $\Delta\phi$ is the phase difference and λ is the wavelength of the radar signal.
The above formulation does not consider the disturbing effects caused by the propagation of the radar signal in the atmosphere and the phase noise yielding to phase shifts. However such terms can be estimated and removed from equation (1).
The main limitation of the interferometric technique is that the deformation measurements refers always to the radar Line Of Sight (LOS), i.e. only the 1D component of the real displacement projected along the LOS can be measured. The radar positioning is thus extremely important: when the LOS of the sensor is parallel to the expected displacement vectors, the system is able to recover the most complete deformation field.
The GBInSAR apparatus adopted for the applications shown in the following chapters is composed of a transreceiver radar head, equipped with a pair of pyramidal horn antennas, hosted on a sledge which moves along a track, thus realizing the synthetic aperture (Figure 2). This apparatus is able to generate microwave signals at definite increasing frequencies sweeping a radiofrequency band, i.e by using the continuous wave step frequency technique (CWSF). The accuracy of the measured phase is usually a fraction of the operated wavelength: by using centimetre wavelengths, millimetre accuracy can be attained. By means of the synthetic aperture and the subsequent treatment of the set of data collected, called focusing, it is possible to produce a 2D image with spatial resolution approximately equal to that obtainable with a real antenna of similar size. The length of the segment along which the radar sensor moves is thus defined as synthetic aperture.
The radar head can be also used as a Real Aperture Radar (RAR) without moving the radar head along the track. In this case only the objects which are contained in the real cone of the antennas will be detected. In particular all the reflecting objects placed at the same distance from the radar head are seen as a unique peak along the power profile of the scenario. Each RAR measurement produces therefore a single 1D profile of the radar echoes intensity (RAR profile) along the LOS of the system. With the RAR it is also possible to perform dynamic measures (up to 100 Hz) in order to retrieve the natural oscillating frequencies of man-made objects and structures (Atzeni et al. 2010; Bartoli et al. 2008; Luzi et al. 2014; Mazzanti et al. 2014) .
All the technical characteristics of the GBInSAR system are summarized in Figure 2.



b)

Central Frequency ν	17.2 GHz
Central Wavelength λ	17.44 mm
Bandwidth B	300 MHz
Synthetic Aperture L	2 m
Track Length	2.5 m
Scan Time Δt	4-7 min
Range Resolution	0.50 m
Cross-Range Resolution	4.4 mrad (4.4 m at 1 Km range)
Antenna type	Horn -20 dB
Antenna Beamwidth (-3dB)	17° (Horiz.) – 15° (Vert.)
Polarization	VV

Figure 2. a) Overview of the GBInSAR system, b) summary of the technical characteristics.

The radar system can be either installed on a stable concrete basement or a rapid positioning system, consisting of portable concrete blocks, can also be adopted (Antolini 2014). The rapid installation of the GBInSAR allows the system to operate in emergency condition when it is fundamental starting the measurements as soon as possible. During a real-time monitoring, the

acquired raw data are focused on site, then target data are extracted based on a previously generated calibration set and sent through a WLAN router to a remote FTP server. The files are further processed on the server. In particular this section is responsible for the atmospheric phase screen estimation and removal, for the phase unwrapping procedure (Ghiglia & Pritt, 1998) and for the displacement estimation. The updated displacement and velocity maps can be successively geocoded and exported in different formats (*.jpeg*, *.mat*, *.txt*) for post-processing purposes. Finally by means of a new software called Early Warning by using Synthetic Aperture Radar (EWuSAR) able to post-process the radar displacement and velocity maps, it is possible to obtain real time hazard maps of the monitored phenomenon (Barla et al. 2014) which can be directly used for risk mitigation.

3. Monitoring of a rock landslide

In this section the application of the GBInSAR technique to monitor the displacement of the Torgiovannetto rockslide in central Italy will be described. This rockslide has developed in a depleted limestone quarry site and it is widely described in literature (Antolini et al. 2015, Barla & Antolini 2015, Brocca et al. 2012, Graziani et al. 2009, Intrieri et al. 2012, Salciarini et al. 2010). The instability affects the whole quarry at different scales but the main problem is related to the stability conditions of a large rock wedge in the upper part of the quarry (Figure 3) with an estimated volume of about 182,000 m^3.

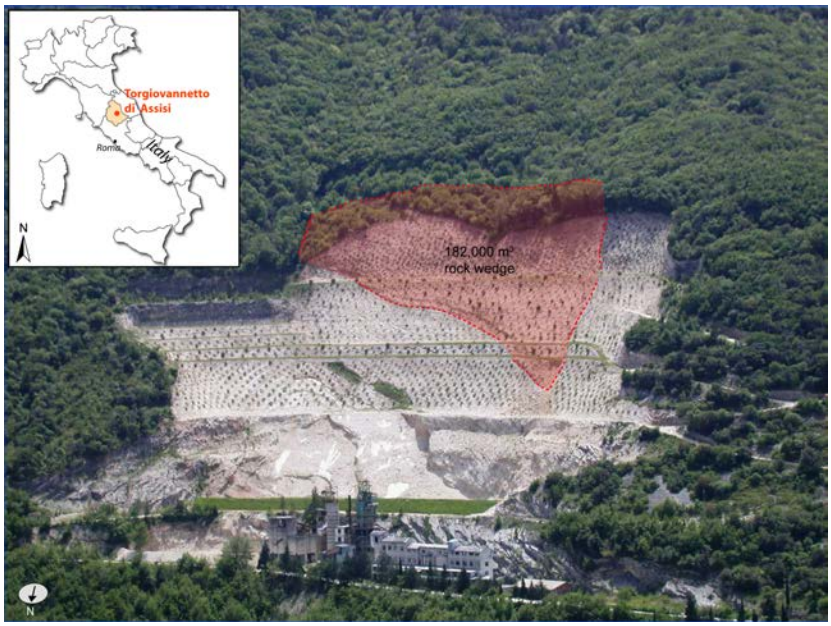


Figure 3. Overview of the Torgiovannetto di Assisi rockslide (Barla & Antolini 2015).

The radar was installed with the light repositioning system on January 31th 2013 at an elevation of about 530 m a.s.l. on the W portion of the Torgiovannetto quarry pit and operated continuously since March 11th, acquiring a total of 1999 SAR images of the scenario (about one image every 30'). The selected location, assured a frontal vision of the monitored scenario with a line of sight approximately parallel to the expected direction of the rock wedge displacements.

The results of the radar monitoring as a mean daily velocity map, georeferenced and projected over a Digital Terrain Model (DTM) of the quarry, is shown in Figure 4a. It is possible to clearly observe the area affected by the movements related to the progressive sliding of the unstable rock wedge (yellow-red pixels) surrounded by stable areas (green pixels). Further limited areas affected by movements are related to the presence of loose debris which lies on the bedrock. The analysis of the map also reveals that the velocity and hence the displacement patterns of the quarry are not uniform. The velocity increases proceeding respectively from W to E and from S to N. These patterns have allowed for the identification of four different landslide's kinematic sectors here referred as "Region of Interest" (ROI). Therefore the GBInSAR results highlighted the presence of differential movements along the main open tension cracks which superimpose over the main rock wedge sliding (Antolini 2014, Barla & Antolini 2015).
Moreover the analysis of the GBInSAR time series allowed for a clear identification of the effects of the rainfalls on the stability of the rock wedge. In Figure 4b the cumulated daily rainfalls versus the measured displacement on three pixel (D1F4, W7 and W8) of the GBInSAR map are shown. Three acceleration phases are evident and they were triggered on the short term period by daily cumulated rainfalls higher than 15 mm. These accelerations of the lower portion of the unstable wedge were also confirmed by the conventional monitoring instrumentation (D1F4 bar extensometer) despite the obvious differences in terms of the measured quantities. Regarding this latter aspect, it is noteworthy that bar extensometer measurements are only point wise while each pixel in the SAR images always refers to an area of some squared meters (depending on the range and cross-range resolution of the system).

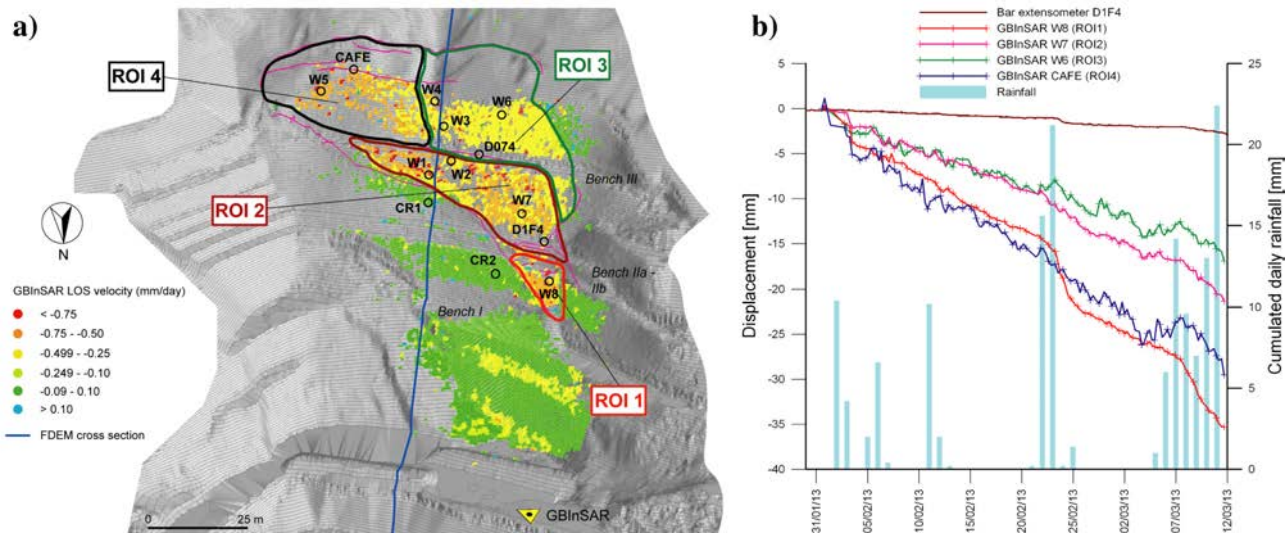


Figure 4. a) GBInSAR velocity map from 31/01/2013 to 11/03/2013 projected over a DEM of the Torgiovannetto quarry with indication of the main tension cracks; b) Cumulated daily rainfalls, extensometer data and GBInSAR time series of some points of the unstable wedge (from Barla & Antolini, 2015).

4. Monitoring tunnel convergences

In order to study the feasibility of application of the radar monitoring technique in underground spaces, a RAR survey was carried out to monitor tunnel convergences of the Turin metro Line 1 (Barla et al. 2011). From March 2010 to October 2011, the construction of the second Railway Link

tunnel took place, just crossing the aforementioned Metro Line 1 tunnel 10-15 m above. In order to allow for the construction in closely controlled conditions and without metro service disruption, an advanced monitoring system was designed and installed in the Metro Line 1 tunnel. The system was capable to measure near real time lining deformations and induced vibrations possibly caused by the excavation workings. The main components of the monitoring system included an Automatic Total Station (ATS), 32 displacement transducers, LVDT type, ten triaxial accelerometers, two thermal transducers and a Real Aperture Radar (RAR) (Figure 5a). The RAR was installed with the main purpose to monitor the deformation of the tunnel lining segment 404 where three artificial reflectors, called also "corner reflectors" were installed in the near vicinity of ATS target points (Figures 5b).

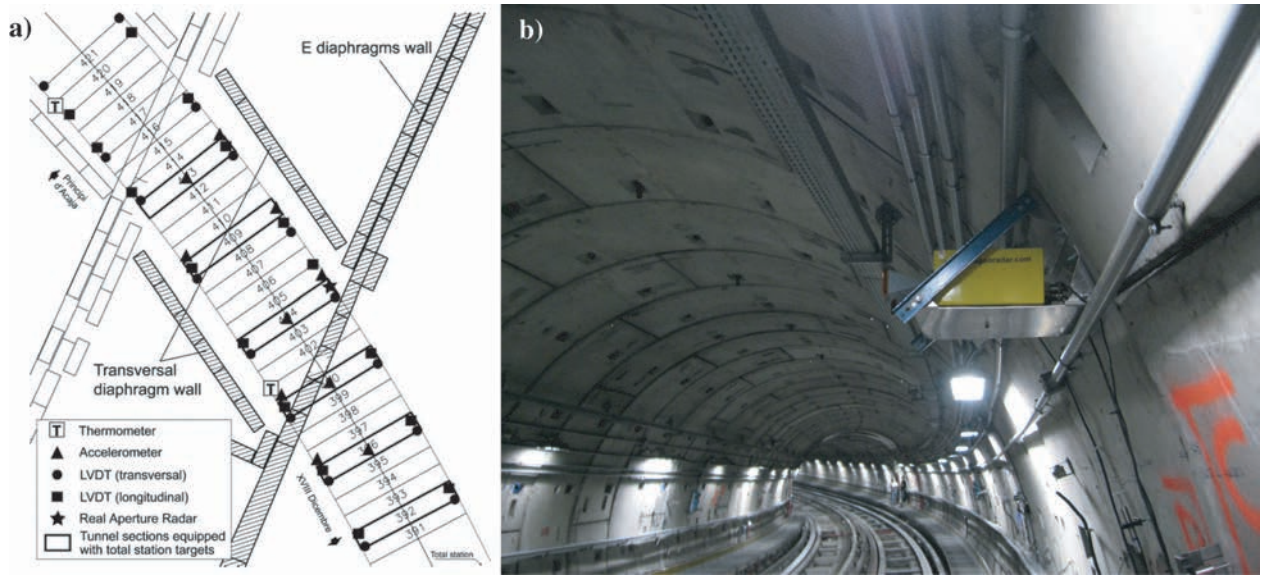


Figure 5. a) Layout of the monitoring system; b) Real Aperture Radar installation (from Barla et al. 2011).

The ATS and RAR units were both equipped with an independent data acquisition and transmission unit. An additional data acquisition system and a transmission unit are used for all the remaining transducers. The acquired measurement data were subsequently transmitted with a wireless router to the Internet. The displacement and temperature transducers were collecting a series of data (34 data points) every 3 min. The ATS needed a total of 60 min for acquiring a complete set of readings of the 62 targets installed in the tunnel, whereas the RAR was monitoring the three corner reflectors installed on the lining segment 404 every 12 min. The accelerometer data were recorded in sequence only when a given target acceleration threshold was reached.

The results of the RAR monitored displacement measured on the three corner reflector CR1, CR2 and CR3 are shown in Figure 6, as well as the position of the corners. In the same figure the convergences measured by the ATS between targets 02-07, 03-07 and 04-07 and the temperature inside the tunnel are shown. It should be noted that both the ATS targets and the corner reflectors were respectively placed in similar positions on the tunnel cross section in order to be able to compare results. Despite the fact that there is not a complete geometrical conformity between the RAR data (displacement measured along the LOS) and the ATS data (variation of the distance between the different targets and target 07), the convergences measured by the two different

systems are shown to be in fair agreement. As shown in Figure 6b the Metro Line 1 tunnel crown moved at first 2 mm downwards due to the stress increase resulting from the placement of the diaphragm walls on both its sides (12-18 June 2010) and then raised up 3-4 mm until June 2011 during the excavation phases of the above Railway Link.

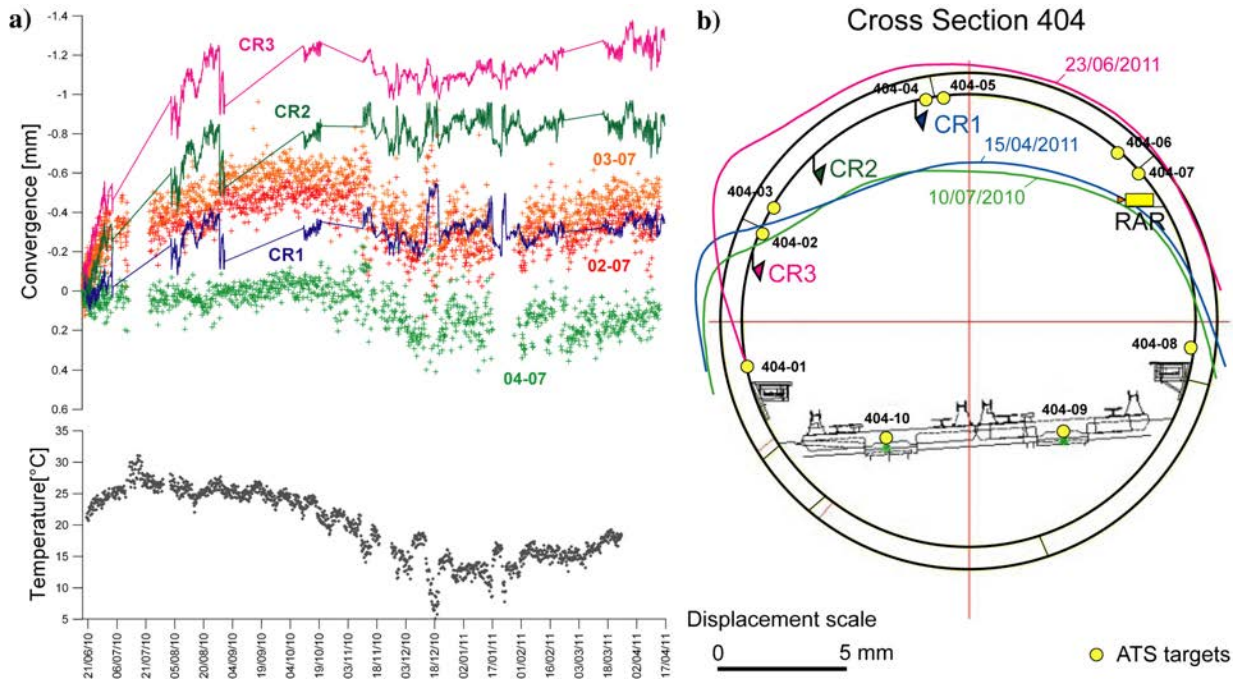


Figure 6. (a) RAR result. Line of sight (LOS) displacements measured on corner reflectors CR1, CR2 and CR3 compared with the ATS convergences measured between targets 02-07, 03-07, 04-07 and temperature; (b) Deformed cross section of the Metro Line 1 tunnel lining segment 404 (from Barla et al. 2011).

5. Monitoring Dam displacements

A further experimental application of the RAR to monitor the displacement of a dam is discussed in this section. The Beauregard dam is located in the Aosta Valley (NW Italy) along the Dora di Valgrisenche river. It was originally a 132 m arch-gravity concrete dam which has now been partially demolished. On the left abutment of the dam a very large Deep Seated Gravitational Slope Deformation (DSGSD) was recognized (Barla et al. 2006, 2010). Since the dam's construction during the fifties, the slow but progressive displacement of the rock mass on the left side of the valley caused a state of structural damage determining relevant implications in terms of civil protection and posing important territorial and environmental issues.

Monitoring for both the dam and the slope dates back to 1960 and was improved and updated in the years 2000 with automatic total station and GBInSAR measurements (Barla et al. 2010). Additionally, a RAR experimental survey was performed to measure the deformations of the different concrete dam cantilevers caused by daily thermal variations. The dam was monitored during a 22 hours time lapse starting on June 11th, 2009 at 12:00 AM. The data were acquired using the RAR at a mean distance of 200 m from the dam mid-point, with the radar system placed on the

right abutment of the downstream dam's face (Figure 7a). Four artificial corner reflectors (D7, D5, D3-S9 and D3-S10) were installed along the dam's crown (Figure 7b) in order to materialize reflective points with an higher signal to noise ratio (SNR). By using such artificial radar reflectors the four points appeared as very high SNR peaks in the power-range profile. The higher the SNR, the higher the accuracy and reliability of the measure.

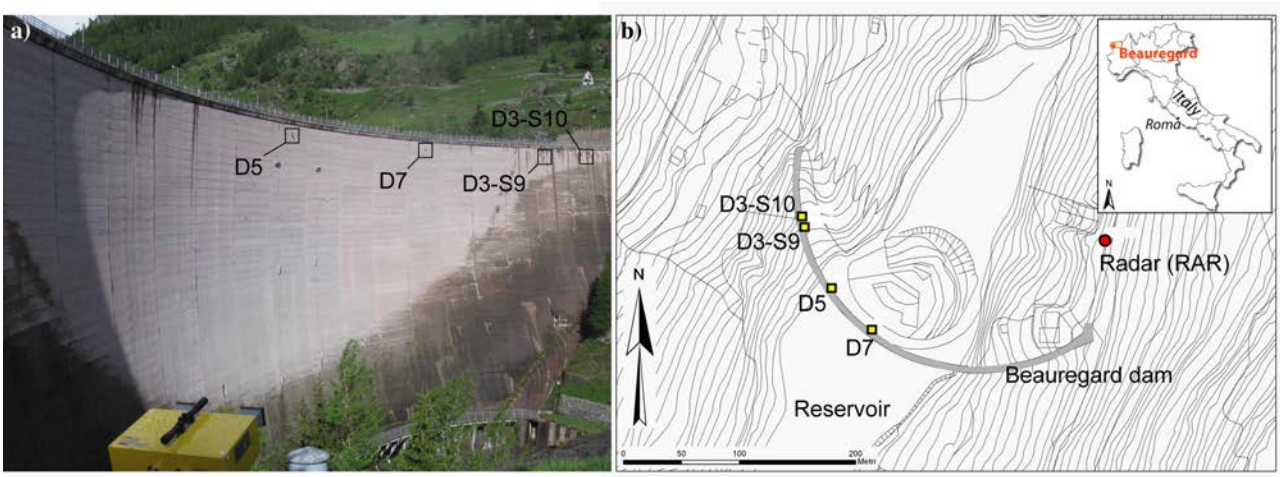


Figure 7. a) Setup of RAR installation; b) Location of the four corner reflectors installed on the Beauregard dam's crown.

The time series profile of three corner reflector points along with the air temperature are shown in Figure 8.

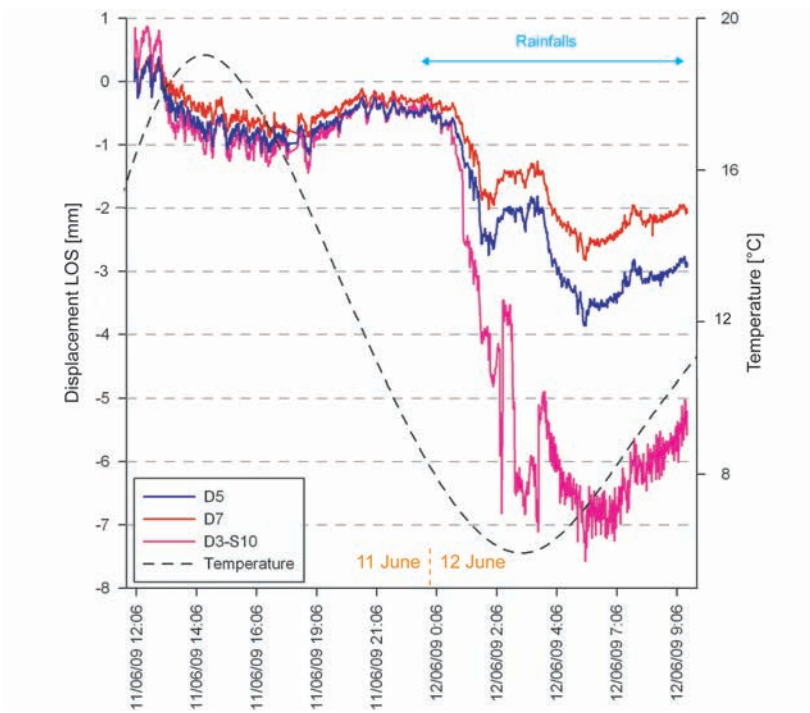


Figure 8. Temporal profile of the displacement measured at four corner reflectors located on the dam crown and air temperature of the Beauregard site.

A cycle of expansion-contraction of the concrete structure up to -1.2 mm caused by the daily thermal variations (about 9°C) is clearly highlighted by all the points of the dam's crown during the first twelve monitoring hours (from 12:00 AM to 12:00 PM of 11 June).
The displacement of the last ten monitoring hours seems instead to be strongly influenced by the heavy rainfalls occurred during the night and the morning of 12th of June (Figure 8). The apparent reverse displacement trend of this time span represents the atmospheric effects on the radar phase signal caused by the rapid increase of the air humidity.

6. Conclusion

The provided examples have shown that the two ground based radar techniques, RAR and SAR, can be successfully adopted to monitor the displacement and the deformation of different geotechnical structures, including natural unstable slopes, man-made objects and infrastructures. The 2D imaging sensor based on the SAR technique couples millimeter accuracy displacement measurements with fine spatial details over the entire surface of the observed area. This is particularly useful to remote monitor natural or engineered slopes and large structures which can be difficult to access or high risky. The RAR approach is instead more adequate and reliable to monitor the displacement of smaller structures. The two examples have demonstrated the feasibility of the application of the RAR in an integrated monitoring network for dams, tunnels and underground spaces.

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