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Integrating radar and laser-based remote sensing techniques for monitoring structural deformation of archaeological monuments

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A B S T R A C T

Ground-Based Synthetic Aperture Radar Interferometry (GBInSAR) and Terrestrial Laser Scanning (TLS) were purposely integrated to obtain 3D interferometric radar point clouds to facilitate the spatial interpretation of displacements affecting archaeological monuments. The paper describes the procedure to implement this integrated approach in the real-world situations of surveillance of archaeological and built heritage. Targeted tests were carried out on the case study of the Domus Tiberiana sited along the northern side of the Palatino Hill in the central archaeological area of Rome, Italy, and displacements of the monument were monitored over almost one year of acquisition. The GBInSAR – TLS integration provided updated information about the condition of the archaeological structures in relation to their history of instability mechanisms, and did not highlighted a general worsening for the stability of the entire monument. Point-wise and prompt detection of displacement anomalies and/or sudden changes in displacement trends proved the suitability of the method to support early warning procedures, also to evaluate effects on the masonry due to human activities.

1. Introduction

Remote sensing technologies are increasingly becoming useful tools for on site preservation of cultural heritage and to constantly update the condition report of a monument. Benefits can be obtained both in situations of ordinary maintenance and emergency surveys. Undertaking preventive diagnostics and monitoring campaigns, i.e. before the execution of any restoration work, is nowadays a sustainable strategy to identify the typology of ongoing deterioration processes and understand the triggering factors (UNESCO, 2010; Fanti et al., in press; Tapete et al., 2012, in press).

Conventional structural monitoring techniques, such as topographic surveys and measurements by means of wall mounted instruments, are still widely used. Nevertheless, such methods only provide point-wise information. Installation might also be a constraint, especially if the condition of the monument to monitor does not allow it or there is a risk for operators' safety. Conversely, ground-based remote sensing techniques can allow these limits to be overcome, thanks to their capability of measuring parameters without a physical contact with the interest object (i.e. non-invasiveness). Also, all the analytical steps – from acquisition phase to automatic data processing – can be managed remotely.

Among the radar-based techniques, Ground-Based Synthetic Aperture Radar Interferometry (GBInSAR) has been hugely tested in environmental applications, for instance to monitor the displacement field of landslide bodies (Antonello et al., 2004), volcanic flanks (Casagli et al., 2010), dynamics of glaciers (Luzi et al., 2007) and instability in mining areas (McHugh et al., 2006). First application for architectural purposes dated in the early 2000s, when the GBInSAR was exploited by the Joint Research Centre (JRC) to monitor the 1:1 scale reproduction of the façade of Palazzo Geraci, in Palermo, Italy. Further advances followed in these last years, and different technologies were developed, including the GBInSAR Lisamobile tested in the present work.

As an imaging technique, the GBInSAR offers the possibility to monitor natural and artificial surfaces with extent up to a few square kilometres, with high sampling frequency of displacement data (up to 1 image every few minutes), sub-millimetre accuracy and metre spatial resolution. The latter parameter is undoubtedly essential to distinguish architectural elements being affected by instability processes from the stable ones.

To overcome the limits of two-dimensional displacement maps, recent works have demonstrated the advantage of projecting the GBInSAR data on Digital Elevation Model (DEM) and Digital Terrain

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Model (DTM) generated from LiDAR point clouds reproducing the observed scene (Gigli et al., 2011; Luzi et al., 2009; Pieraccini et al., 2006). While Airborne Laser Scanning (ALS) is suitable for topographic survey of huge natural environments and for wide-area archaeological investigations (Lasaponara et al., 2010; Lasaponara and Masini, 2011), Terrestrial Laser Scanning (TLS) was found more adaptable for acquisition of the three-dimensional geometry of single monuments or group of buildings (Gigli et al., 2009). Non-invasiveness, reduced acquisition times, high accuracy and spatial resolution have opened to an extensive use of TLS in the field of cultural heritage, making it a routine device for architectural and archaeological documentation and building rendering (English Heritage, 2007; Lerma et al., 2010; Yastikli, 2007). TLS 3D models constitute optimal geometric supports for a more precise localization of the monitoring measures within the x–y–z space, allowing an immediate georeferencing of the superficial deformation detected over the monitored monuments.

Although the final outputs of the two techniques substantially differ in the dimensional configuration of the information provided (2D for GBInSAR data, 3D for TLS models), their integration is useful to improve the quality and reliability of monitoring campaigns on monuments and historical buildings.

In this paper we propose a non-invasive methodology integrating GBInSAR and TLS data to perform real-time monitoring of superficial deformation affecting archaeological and built heritage. After an overview of both the techniques, all the operational phases of GBInSAR – TLS integration are illustrated, starting from the preliminary choice of the site for the instrumentation installation to the processing of the final mapping output (the so-called "3D interferometric radar point clouds and models"). The results obtained during the monitoring campaign of the Domus Tiberiana within the central archaeological area of Rome, Italy, are here presented to critically discuss potentials and limits of this methodology, with specific regard to capabilities for activities of daily surveillance and warning in archaeological contexts.

2. The tested techniques

2.1. Ground-based radar interferometry (GBInSAR)

Synthetic Aperture Radar Interferometry (InSAR) is a non-invasive imaging technique which allows the detection of superficial deformation affecting natural and artificial environments/objects, based on the calculation of the phase difference of the collected radar signal between two SAR images covering the same scenario.

The active radar sensor is installed on a ground-based platform (that guarantees the ideal condition of zero baseline geometry) and it is equipped with two antennas. One transmits pulsed microwaves and one receives the echo backscattered by surfaces of the observed object, while the sensor moves along a linear rail of a certain length (usually 1–3 m; Fig. 1a). This configuration allows the acquisition of radar images of the observed scene following the principle of Synthetic Aperture Radar (Rosen et al., 2000), with generation of topography-free interferograms and quantitative estimation of the occurred displacement for each point (Tarchi et al., 2003). Each SAR image collected at a certain time is a two-dimensional map of the observed scene obtained by combining the spatial resolution along two directions: (i) the range resolution (ΔRr), along the direction perpendicular to the rail; (ii) and the azimuth resolution (or cross-range; ΔRaz), parallel to the synthetic aperture (Luzi, 2010; Fig. 2a).

Under the conditions of zero baseline and negligible decorrelation due to propagation and scattering phenomena (i.e. coherence value approximately of 1), the interferometric phase is directly related to the variation of the sensor-target distance. It means that the displacements occurred during the time elapsed between two or more subsequent coherent SAR acquisitions, can be effectively estimated along the Line Of Sight (LOS) of the radar sensor (Fig. 1b).

According to the specific acquisition geometry, only the component along the LOS (D_{LOS}) of the real displacement vector (D) can be estimated. Displacements along a direction parallel to the LOS are better estimated (D_{LOS} is equal to D), while those along perpendicular direction are missed (D_{LOS} is zero) (Fig. 1b).

This is one of the major limits of the technique. Hence, the choice of the installation site is essential and frequently requires a preliminary evaluation of the expected major directions of displacement. On the other hand, the high portability of the current models of GBInSAR instrumentation allows best acquisition geometry to be set up, thereby approaching the ideal condition of parallelism between the LOS and the hypothesized direction of the major vector component of the displacement.

Regarding the sensitivity, the radar operates at microwave frequencies ranging from 12 to 18 GHz and corresponding wavelengths of 2.50–1.67 cm (K_u band, according to IEEE Std 521–2002), and can ensure millimetre up to sub-millimetre accuracy.

Objects up to few square kilometres of extent can be monitored from distances up to thousand of metres. Although the cross-range resolution of SAR images varies within the observed scene due to the measurement distance, good acquisition geometries can lead to fine resolution in range better the 1 m.

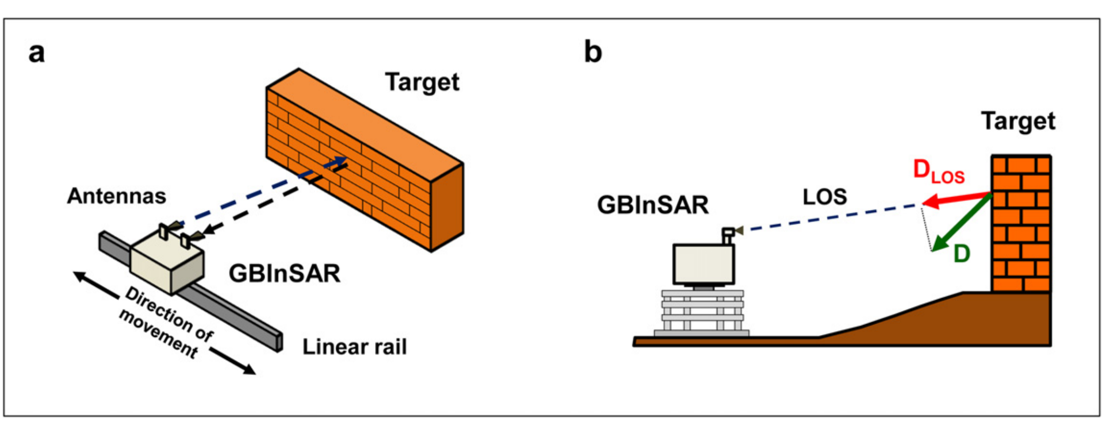

Fig. 1. Scheme of: a) SAR image acquisition by the GBInSAR, which collects the microwave signal backscattered by the irradiated object while moving along the linear rail; and b) measurement of the component along the Line Of Sight (LOS) of the sensor (D_{LOS}) of the real displacement vector (D) affecting the monitored object.