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Remote Sensing Measurements for the Structural Monitoring of Historical Masonry Bridges

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Abstract. Advances in data processing and the availability of larger SAR datasets from various high-resolution (X-Band) satellite missions have consolidated the use of the Multi-Temporal Interferometric Synthetic Aperture Radar (MT-InSAR) technique in the near-real-time assessment of bridges and the health monitoring of transport infrastructures. This research aims to investigate the viability of a novel non-destructive health-monitoring approach based on satellite remote sensing techniques for structural assessment of bridges and the prevention of damage by structural subsidence. To this purpose, commercial high-resolution TerraSAR-X (TSX) products of the German Aerospace Centre (DLR) provided by the European Space Agency (ESA), were acquired and processed by MT-InSAR technique. Analyses were developed to identify and monitor the structural displacements of the historical "Ponte Sisto" masonry bridge located in Rome, Italy, crossing the Tiber River. To this extent, the historical time-series of deformations were processed by Persistent Scatterers (PSs) relevant to critical structural elements of the bridge (i.e., bridge piers and arcs). A novel data interpretation approach is proposed based on the selection of several PS data-points with coherent deformation trends and location on the bridge. The outcomes of this study demonstrate that multi-temporal InSAR remote sensing techniques can be applied to complement non-destructive ground-based analyses (e.g., ground-penetrating radars, laser scanners, accelerometers), paving the way for future integrated approaches in the smart monitoring of infrastructure assets.

Keywords: remote sensing, bridge monitoring, PSI, cultural heritage monitoring, masonry bridges, non-destructive assessment.

1. Introduction

Monitoring the conditions of transport infrastructures, such as railways, roads and bridges, is a priority for asset owners and administrators to ensure structural stability, operational safety and to prevent damage and deterioration. Failing to comply with these requirements can lead to expensive rehabilitation or even failures or collapses [1]. Currently, several on-site non-destructive testing (NDT) technologies and sensors are available for subsidence monitoring and displacement mapping. Amongst others, accelerometers [2], strain gauges [3], topographic levelling [4], Global Position System (GPS), [5], Ground Penetrating Radar (GPR) [6-8], Microwave Healing [9, 10], Infrared Thermography (IRT) [11] and terrestrial SAR Interferometry [12], are recognised as viable technologies for infrastructure monitoring and preventive maintenance operations.

However, on-site surveys are costly and typically complex to apply at the network level due to economic and administrative constraints. To overcome this limitation, several innovative satellite-based remote sensing techniques, e.g., the Persistent Scatterers Interferometry (PSI) among which the PS-InSAR [13, 14] and the Small BAseline Subset (SBAS) [15], have gained momentum in the last few years for the monitoring of transportation assets and the investigation of urban areas.

The definition of a comphrensive methodology for the evaluation of the structural reliability, robustness, and resilience of historical bridges, is still an open-issue. In this context, innovative solutions (e.g. non-destructive testing (NDT) methods) are being increasingly used to comply with the constraints and limitations in the monitoring operations of historical bridges, where sampling or digging parts of the structure is very limited or not possible at all.

2. Aim and Objectives

This research aims at demonstrating the viability of the high-resolution Synthetic Aperture Radar (SAR) imagery for the monitoring of a historic masonry bridge in Rome, (Italy), and the effective detection of critical information, e.g., displacements on structural elements of the bridge, including the long-term deformation trends due to foundation settlements and anomalous seasonal variations by flood/temperature facors during the observation period.

The main objective is to verify the viability of the high-resolution X-Band data to identify features of interest for use with complementary in-situ investigations and the provision of strategic information to asset owners (e.g. the Municipality of Rome) for maintenance purposes. Within this framework, this study reports an innovative approach, based on the combined use of the high-resolution SAR imagery products of the Italian constellation of satellites "COSMO-SkyMed" and the German satellite mission "TerraSAR-X" (X-Band).

3. Methodology

3.1. Historical Bridge Monitoring by Multi-Temporal InSAR

The working framework of the Multi-Temporal Interferometric Synthetic Aperture Radar (MT-InSAR) technique relies on a statistical analysis of the signals emitted by the on-satellite sensor and back-scattered by a network of coherent targets on the ground, i.e., the Persistent Scatterers (PSs). This approach allows to estimate the displacements occurred between different acquisitions by a separation between the phase shift related to the ground motions and the phase component due to the atmosphere, the topography and the signal noise contributions [13, 14].

An advantage of these techniques is the relatively lighter data-processing required for the assessment of displacements and the detection of critical areas, as opposed to the higher computational load needed in other approaches. Therefore, the MT-InSAR approach has proven useful in monitoring of transport infrastructure, as the high-density of radar-stable-targets, allows for accurate measurements of displacements with a millimetre accuracy. To this effect, several scientific contributions related to the application of the PSI techniques can be found in the literature, as reported in Tab. 1.

Table 1. Main applications of the PSI techniques by different infrastructures types.

Infrastructure type	References
Bridges	[16-20]
Railways	[21-26]
Highways and tunnels	[27-29]
Airport runways	[30-34]

This evidence confirms that the use of satellite remote sensing techniques in these areas of endeavour is becoming a popular asset management tool.

Satellite remote sensing has been acknowledged in the literature as an effective technology for measuring displacements due to natural hazards. However, its application in routine monitoring of civil infrastructures, including the monitoring of historical bridges, is still an open issue.

In this context, the historical "Ponte Sisto" river masonry bridge located in Rome, Italy, is investigated. The proposed method aims to cover an existing gap-in-knowledge in the provision of localised and high-resolution information on historical bridge deformations, and the reconstruction of their time series. Furthermore, a novel post-processing interpretation approach based on data-clustering algorithms is presented to allocate each PS data-point to relevant sub-groups, based on deformation trend and localisation-to-structural-element criteria.

4. Experimental Framework

4.1 The Case Study: the Ponte Sisto Masonry Bridge

The first bridge built in modern times, was built by Pope Sisto IV della Rovere for the Jubilee in 1475, to allow direct communication between the Trastevere district (and the Vatican) and rest of the city. The masonry structure is made up of several blocks of tuff, covered by travertine marble. Currently, the bridge, which is 108 metres long and 11 metres wide, is restricted to pedestrians traffic. The bridge consists of four arches covered with travertine, with a circular opening on the central pylon, to decrease the water pressure in the event of a flood, and five papal coats of arms in marble for decoration. [35].

Under Pope Pius IV in 1567, the first rehabilitation works were carried out by reinforcing one of the pillars. Following a damage from a flood in 1598 under Pope Clement VIII, new restorations were carried out on the pavement and the parapets. In 1877, the bridge was enlarged with hanging sidewalks in cast iron resting on corbels with new parapets. Parallel to this, it was decided to increase the section of the bridge by adding two metal walkways suspended on corbels along the sides. More recently, a restoration project was implemented to remove the nineteenth-century metal structures and constructing the new parapets [35].

Fig. 1 –Ponte Sisto, (1471 A.D.), Rome, Italy

4.2 SAR Datasets

Two datasets of X-Band SAR data were collected and processed by the PSI technique to quantify and evaluate potential displacements on the inspected bridge. The COSMO-SkyMed SAR products (X-Band) were provided by the Italian Space Agency (ASI) and had been processed with the PS-InSAR technique by TRE Altamira [14] within the framework of the “Piano Straordinario di Telerilevamento Ambientale” (PST-A), a project of the Italian Ministry for Environment, Land and Sea Protection (MATTM) [36]. More specifically, the PSs, which were delivered under the license to use, have been calculated by processing of 35 SAR products collected in the period from 2011 to 2014.

A further assessment of the area was performed in this study through the processing of X-Band SAR images collected by the TerraSAR-X mission. These products were acquired in the framework of the Project "IMA-BA (Id.56598)" approved by the European Space Agency (ESA), and delivered by the German Aerospace Centre (DLR) under the license to use. The TerraSAR-X system operates in X-band at a frequency of 9.6 GHz corresponding to a wavelength of 3.1 cm. In this analysis, the Persistent Scatterers were derived by the processing of 20 TerraSAR-X SAR products collected in the period from 2017 to 2019.

4.3 PSI Processing

The SAR datasets were processed according to the PSI method [10] by means of the commercial Software SARPROZ © [37, 38]. More specifically, the PSI technique operates by the application of a multi-stage approach [13, 14]. As a result, various stable reflectors can be identified over the inspected area and located on the bridge. However, SAR satellites can only detect displacements in the Line-of-Sight (LoS), with reference to a specific orbit-related incident angle. Therefore, the displacement detected is a component of the real displacement that occurred on the ground. Different approaches were proposed to evaluate the real displacements-velocity-vector, from datasets acquired in different acquisition geometries (i.e., Ascending and Descending) [39, 40].
In regard to the investigated area, SAR images in the only descending acquisition geometries (i.e. the SAR moves from North to South) were used for both the TerraSAR-X and COSMO-SkyMed missions, in the observation period of this study. Accordingly, the results reported in this paper refer to values of displacement calculated along the LoS direction of the relevant sensor.

5. Results and Short Discussion

Several PSs were identified over the inspected Bridge. The set of PSs resulting from the PSI analysis COSMO-SkyMed from July 2011 to April 2014 and TerraSAR-X products (descending geometry) from September 2017 to January 2019 are showed in Fig. 2 (a, b).

The identified PSs have been exported into a GIS platform and displayed in relation to the average velocity motion.

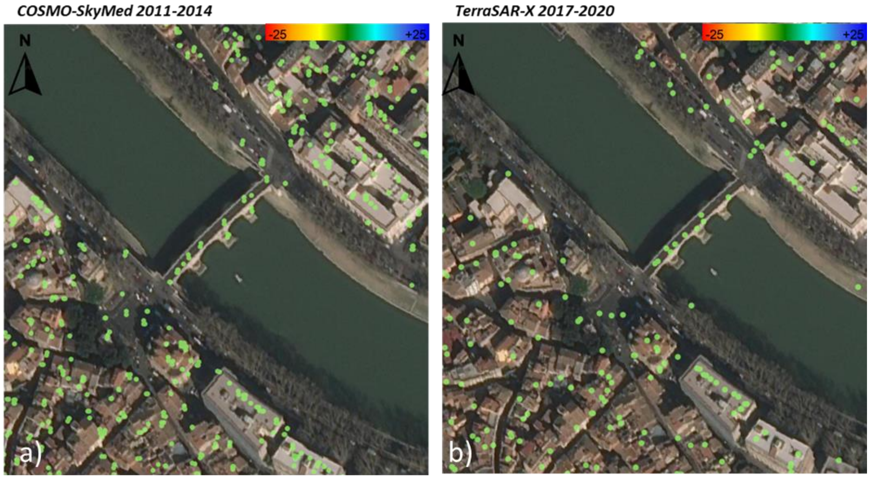

Fig. 2. PSI results collected on Ponte Sisto. Data are displayed in relation to the average trend of velocity and expressed in mm/yr: a) PS outputs by the COSMO-SkyMed Product (©ASI – Italian Space Agency)- PST-A; b): detailed results of the TerraSAR-X Products (© DLR-German Aerospace Agency).

Fig. 3 shows several PS located over the bridge, characterised by a seasonal deformation trend in both the SAR datasets. The grey area represents the domain of max. and min, whereas the red dots represent the mean values of the deformation for the selected cluster.

The average velocity-value over 32 months of investigation (from July 2011 to March 2014) for this occurrence is -0.6 mm/yr for the COSMO-SkyMed dataset, which proves that deformations related to the structural elements of the bridge (e.g. piers and archs) were not particularly critical. Moreover, the TerraSAR-X average velocity value calculated over 30 months of investigation (from December 2017 to June 2020) is –1.7 mm/yr, proving an increment of the deformations of approximately 1.1 mm/yr.

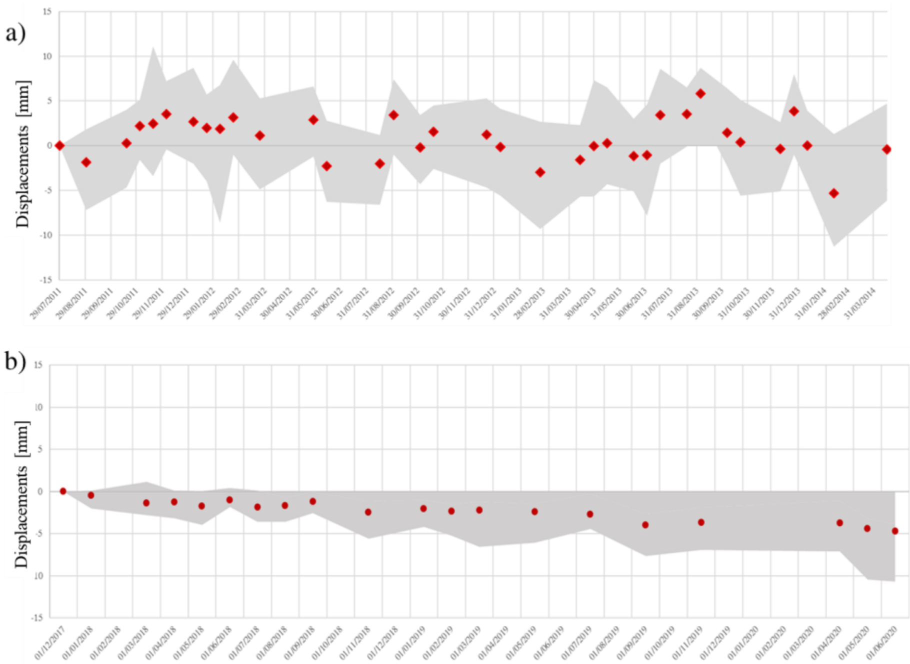

Fig. 3. PSI time-series and deformation velocity from: a) PS samples related to the COSMO-SkyMed, (©ASI –2011-2014)- PST-A project; b). PS time-series of the TerraSAR-X Products (© DLR-German Aerospace Agency).SAR images provided by ESA

Furthermore, the analysis of deformations occurred to the bridge was complemented by the information collected on the geological settings of the area, reported in the Fig. 4. The blue areas in the figure represent soft soils (e.g. clay and limes) with a low bearing capacity of the subgrade. The red area indicates the location of the Ponte Sisto Bridge.

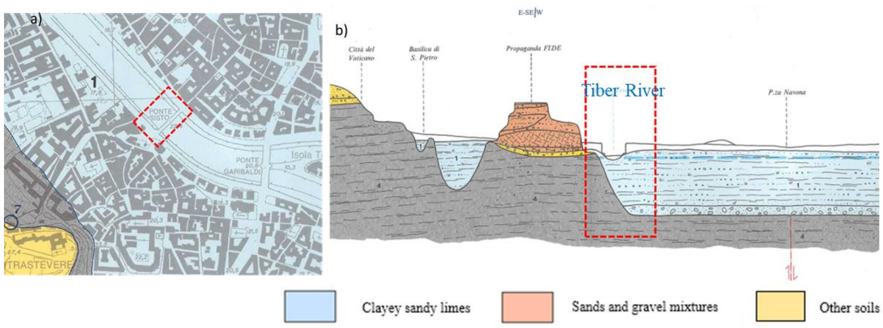

Fig. 4. Geological setting of the inspected Areas of interest: a) location of the "Ponte Sisto" bridge and b) cross section of the geological settings

6. Conclusions and future prospects

This research demonstrates the capability of the Persistent Scatterers Interferometry (PSI) remote-sensing technique to be used as an innovative approach for the structural monitoring of historical masonry bridges. To this purpose, PS time-series of the X-Band COSMO-SkyMed products, provided by the Italian Space Agency (ASI), were acquired in the framework of the PST-A project of the Italian Ministry for Environment, Land and Sea Protection (MATTM). Furthermore, TerraSAR-X products provided by the European Space Agency (ESA) and the German Aerospace Centre (DLR), wereprocessed by means of a PSI analysis, to monitor the structural deformations of the "Ponte Sisto" bridge, a masonry bridge of historical value.

With reference to the discussed methodology, the presented multi-temporal PSI technique was effective at detecting several Persistent Scatterers (PS) over the bridge, confirming its capability in the monitoring of historical bridges.

Both the satellite datasets highlight the presence of seasonal components of the deformations. These were more evident in the COSMO-SkyMed dataset, as this includes a higher amount of satellite images within the same investigated time interval.

This analysis paves the way to implement further analyses on the potential causes of structural displacements (e.g. temperature, river-flows). Information arising from these investiations can be therefore complemented with on-site surveys and in-situ inspections. This evidence is of interest for a prospective integration with complementary non-destructive data collected on-site (e.g., levelling, displacement sensors, linear variable displacement transformer (LVDT) or ground penetrating radar (GPR)), and in-situ visual inspections of the bridge. This will allow to investigate further about the source of displacements detected by PSI and, hence, for a more effective planning of preventive maintenance on historic masonry bridges to limit full rehabilitation activities.

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