Spaceborne remote sensing for transport infrastructure monitoring: a case study of the Rochester Bridge, UK

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SPACEBORNE REMOTE SENSING FOR TRANSPORT INFRASTRUCTURE MONITORING: A CASE STUDY OF THE ROCHESTER BRIDGE, UK

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ABSTRACT

This study presents a novel bridge monitoring approach for transport assets, based on the synergistic use of high-resolution (X-band) SAR imagery. A multi-temporal SAR Interferometry analysis is performed to detect potential issues related to the Rochester Bridge, located in Rochester, UK. A displacement map for the structure was produced using space-based SAR measurements acquired by the Italian constellation COSMO-SkyMed over the period 2017–2019, provided by the Italian Space Agency (ASI) in the framework of the Open-call for Science Project "Motib – ID742". The outcomes of this study demonstrate that multi-temporal InSAR remote sensing techniques can be applied to complement information from non-destructive ground-based methods (e.g., ground-penetrating radars, laser scanners, accelerometers, etc.), paving the way for future integrated approaches in the smart monitoring of infrastructure assets.

***Index Terms*—** Remote Sensing, COSMO-SkyMed, Persistent Scatterers Interferometry, Bridge Monitoring, Non-Destructive Assessment, Transport Infrastructure Monitoring, InSAR, Satellite Remote Sensing.

1. INTRODUCTION

Monitoring the conditions of transport infrastructure, such as railways, roads and bridges, is a priority for asset owners and administrators to ensure structural stability, operational safety and prevent damage and deterioration - leading to expensive rehabilitation or even failures or collapses [1]. Currently, several on-site non-destructive testing (NDT) technologies and sensors are available for real-time and effective subsidence monitoring and displacement mapping. Amongst the others, accelerometers [2], strain gauges [3], Global Position System (GPS), levelling [4], Ground Penetrating Radar (GPR) [5-7], Infrared Thermography (IRT) [8] and terrestrial SAR Interferometry [9], are recognised as viable technologies for infrastructure monitoring. However, on-site surveys are costly and are difficult to implement at the network level due to economic and administrative budget constraints. To overcome this limitation, several innovative satellite-based remote sensing techniques, i.e., the Persistent Scatterers Interferometry (PSI) amongst which the PS-InSAR [10,11] and the Small BAseline Subset (SBAS) [12], have gained momentum in the last few years for the monitoring of transport assets and the investigation of nearby areas.

2. AIMS AND OBJECTIVES

This research aims to demonstrate the effectiveness of using high-resolution SAR imagery for accurate transport asset and bridge monitoring. The viability of high-resolution X-band SAR products for detection of features of interest is analysed for further integration with datasets from complementary ground-based NDT techniques (e.g., GPR, laser scanner). For this purpose, this study reports an experimental monitoring activity based on the use of high-resolution COSMO-SkyMed (X-band) SAR imagery.

3. METHODOLOGY

3.1. Multi-Temporal InSAR for Transport Infrastructure Monitoring

Multi-temporal Interferometric Synthetic Aperture Radar (MT-InSAR) techniques are becoming crucial for the investigation of ground, structure and infrastructure deformations. The rising popularity is also due to the provision of new space missions with the last generation of X-band SAR sensors (e.g., COSMO-SkyMed, TerraSAR-X, PAZ), able to provide high spatial resolution (about 3×3 m to 1×1 m), revisiting-time (up to 4 days) and displacement accuracy (millimetre scale). The working framework of the 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 across different acquisitions by a separation between the phase shift from the ground motions and the phase component due to atmospheric, topographic and signal noise contributions [11,12]. An advantage of these techniques is the relatively rapid 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 method has proven to be ideal in monitoring transport infrastructure, as the high density of radar stable targets allows for more accurate measurements. With such cost-benefit ratio, if adopted by technical offices of local administrations, MT-InSAR can contribute towards a more efficient monitoring of urban transport infrastructure towards cities' resilience and sustainability, as targeted by the United Nations' 2030 Agenda Sustainable Development Goal #11. To this effect, several scientific contributions in this area about successful MT-InSAR applications can be found in the literature, as reported in Tab. 1.

Tab. 1 –PSI applications for transport infrastructure monitoring

Infrastructure type	References
Railways	[13-17]
Bridges and viaducts	[18-24]
Highways and tunnels	[25,26]
Airport runways	[27-29]

This evidence confirms that satellite-based remote sensing techniques are becoming a popular asset management tool for use in these areas of endeavour. SAR satellites can detect displacements in the Line-of-Sight (LoS) of the sensor, with reference to the specific orbit-related incident angle. Therefore, the detected displacement along one viewing geometry is a component of the real displacement occurred on the ground. Different methods have been proposed in the literature to overcome this limitation and evaluate the real displacement-velocity-vector and its components. This is achieved by combining the information on the components of the PS from the same structure, if two datasets acquired in different acquisition geometries (i.e., Ascending and Descending) are available [30,31].

4. EXPERIMENTAL FRAMEWORK

4.1 The Case Study

To achieve the above-set objectives, a dataset of SAR images from ASI's COSMO-SkyMed mission covering the area of Rochester in Southeast England (UK), was collected in the time interval 2017–2019, and processed using the PSI technique. Data in this study are referred to the Rochester Bridge, a nineteenth-century bridge, crossing the River Medway and connecting the towns of Strood and Rochester. There have been several configurations of the bridge, with the "current" bridge being actually composed by four separate bridges. The "Old" bridge and the "New" bridge carrying the A2 road, the "Service" bridge carrying service pipes and cables are owned, maintained and managed by the Rochester Bridge Trust [32], whereas the "Railway" bridge - carrying the railway - is owned by Network Rail. It was reconstructed between 1910 and 1914, and arches were installed at their present position above the roadway, to provide a larger clearance for ships movement under the bridge. Between 1965 and 1970, the Rochester Bridge Trust built a second roadway bridge on the piers of the disused railway bridge, immediately downstream from the roadway bridge. The reconstructed Victorian bridge is nowadays known as the "Old Bridge", whereas the second roadway bridge is known as the "New Bridge".

Fig. 1 – The Rochester Bridge, UK

4.2 SAR Datasets

A dataset of 40 high-resolution COSMO-SkyMed SAR Stripmap Himage scenes was collected, in a descending geometry, and delivered by ASI under a license to use, in the framework of the Project "MoTIB, ID 742", (COSMO-SkyMed©- Open Call for Science). The COSMO-SkyMed system operates in X-band at a frequency of 9.6 GHz corresponding to a wavelength of 3.1 cm. This allows to collect data with ground-resolution cells sized 3×3 m and detect displacements with a millimetre accuracy, under ideal conditions [33-36]. As the COSMO-SkyMed archive relies on a single acquisition geometry, at this stage of the research we will only refer to displacements detected along the LoS of the satellite.

Tab. 2 – SAR dataset characteristics

	COSMO-SkyMed (ASI)
Time Period	01/2017–12/2019
Operating Frequency	X-Band (9.6 GHz)
Wavelength	λ =3.1 cm
Range / Azimuth Resolution	3 m / 3m
Acquisition Mode	Stripmap Himage
Processing Level	L1A- Single look Complex

A PSI analysis was developed to detect and monitor structural displacements of the bridge and achieve useful information for integration with on-site inspections in future analyses. It is worthy to recall that in the monitoring of critical structures, such as bridges, measurement accuracy is a key factor to identify critical displacements and achieve a more accurate interpretation of results. However, the provision of high-resolution archive datasets must be regarded as a unique historical source of information, that cannot be collected with any other available on-site equipment. Therefore, the analysis of these outcomes is fundamental for the development of future investigations and new algorithms for assessment of transport infrastructure. The COSMO-SkyMed dataset was processed according to the PSI method [11,12] by means of the "Interferometric Stacking Module" of the Software SARscape®, integrated in the Software ENVI® [37]. More specifically, the PSI technique operates by the application of a multi-stage approach, based on a sequence of consecutive processing stages [11,37]. As a result, stable reflectors, i.e., the PSs, can be identified over the inspected area.

5. RESULTS AND SHORT DISCUSSION

Concerning the methodology described in section 3, the presented multi-temporal PSI technique was effective at detecting several PSs associated to the investigated bridge. Results from the processing of the COSMO-SkyMed (CSK) data (descending geometry) are shown in Fig.2. The analysis allowed to obtain several PSs over the entire bridge structure. The outputs were converted in a vector file format, imported into a GIS platform and displayed as a function of the average velocity vector. The green points are referred to stable scatterers with a displacement velocity ranging from -4 mm/yr and +4 mm/yr. By analysing the velocity of motion and the historical time-series of deformation, no critical issues (e.g., subsidence) were identified. Several PSs show a comparable deformation trend and appear to be affected by cyclic down-lifting and up-lifting trends, most likely related to seasonal effects.

Fig. 2 – PSI results obtained over the Rochester Bridge, UK

For each acquisition, the relative position of the PS referred to as a stable Ground Control Point (GCP) is known. The GCP is statistically detected, and it is located externally from the bridge, which was assumed to be stable for the investigated time-period. To quantitatively evaluate the PSI results, the profile of the spatial distributions of the average deformation velocity (mm/yr) related to the PSs on the road bridge, along the longitudinal axis, is shown (Fig.3 b, c).

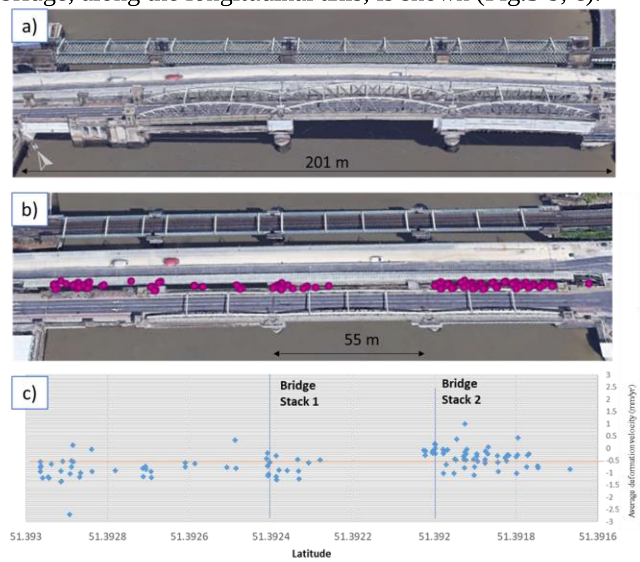

Fig.3 Overview of: (a) the Rochester Bridge (Google Earth©); b) PS selection on the road bridge; c) displacement rate (mm/year) calculated from CSK PSI and profile of the spatial distributions of the deformation velocity (mm/yr) estimated from CSK PSI (2017-2019) in the Line-of-Sight.

No critical displacements rate values were identified by the PSI technique. The values of motion are between +1.5 mm/yr and -2.6 mm/yr. This reasonably excludes any serious long-term deformation within the two years and eleven months of investigation (2017-2019). Results confirm the possibility to detect and monitor several PS coherent points by the MT-InSAR approach over a significant observation time. This is crucial to integrate information with on-site inspections and data obtained using ground-based NDT and Machine Learning algorithms [38,39].

6. CONCLUSION

This research demonstrates the potential of using PSI remote-sensing technique as a mean to monitor transport infrastructure and bridges with a sustainable benefit-cost ratio. To this purpose, X-band COSMO-SkyMed products provided by ASI were acquired and processed. Results demonstrate the viability to detect several Persistent Scatterers (PSs) over the Rochester Bridge across a significant observation time. This information is fundamental to improve upon the capacity of Bridge Management Systems (BMS), by prediction of critical displacements and optimization of maintenance before structural failure. This research paves the way to further investigations, as well as to the implementation of an integrated methodology for assessment and monitoring of bridges.

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