Satellite InSAR Technology for Displacements Monitoring of Bridges: A Comparison with On-site Topographic Measurements and Uncertainty Quantification

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ABSTRACT

Satellites equipped with Synthetic Aperture Radar (SAR) sensors can capture millimetre-scale displacement of the Earth's surface and man-made structures regardless of atmospheric conditions or lighting. Over the past two decades, Interferometric SAR (InSAR) has found many applications, including monitoring subsidence, volcanoes, and glaciers. While there have been some applications in civil engineering, a metrological validation of satellite technology for remote structural health monitoring (SHM) compared to traditional on-site SHM is lacking or inconclusive. This research aims to validate the use of satellite based InSAR technology for SHM of road bridges by directly comparing the time series of displacement extracted with InSAR on the Colle Isarco Viaduct, Italy, with those obtained by on-site topographic monitoring. This study also compares the deformed shape of a subpart of the bridge, which is modelled based on satellite and on-site measurements, to verify the possibility of reconstructing the bridge distortion over time based only on satellite data. The goal is to analyse this new technology's accuracy and reliability and identify its strengths and limitations. If deemed reliable, this technology could simultaneously monitor many civil infrastructures at a significantly lower cost than traditional site monitoring systems.

INTRODUCTION

Bridge managers commonly rely on periodic visual inspections to assess bridge conditions and prioritize maintenance interventions. However, this approach is time-consuming, subjective, and limited to highly degraded bridges, potentially missing damage initiation and propagation. Structural Health Monitoring (SHM) offer accurate and objective information about bridges condition state [1],[2]. However, the high cost of SHM systems still hinder their deployment to the most critical bridges.

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In the last years, satellite Interferometric Synthetic Aperture Radar (InSAR) has gained attention in bridge SHM research community [3]. Specifically, Multi-Temporal InSAR (MT-InSAR) analyzes satellite SAR images and measures millimetric movements of reflective targets on the ground [4], [5]. MT-InSAR has been successfully applied to subsidence monitoring and seismology [6]–[8]. However, the literature lacks systematic validations of InSAR-based SHM for bridges, which limits this monitoring technique to research studies rather than to widespread use by practitioners.

This article addresses this gap by providing a comprehensive metrological validation of InSAR-based bridge SHM using the Colle Isarco Viaduct as a case study. The study compares (a) the displacement time series of optical prisms located on the viaduct and acquired from an on-site topographic SHM system with (b) displacement time series of reflective targets – Persistent Scatterers (PSs) – extracted from SAR images acquired from the COSMO-SkyMed satellite mission.

The study consists of five consecutive tasks: (1) extraction of displacements time series of optical prisms measured through the on-site topographic system; (2) extraction of displacements time series of PSs belonging to the viaduct; (3) direct comparison of those displacement time series to quantify the uncertainty; (4) definition of a kinematic structural model of the main span of the bridge and calibration based separately on topographic and InSAR data, followed by a comparison of the time-dependent deformations; and (5) calibration of the kinematic structural model through data fusion of SAR images and topographic measurements to solve phase unwrapping problems characterizing bridge sections with the greatest displacements.

CASE STUDY

The Colle Isarco Viaduct is a prestressed concrete bridge located in Italy, built in 1968 and opened to traffic in 1971. It has a total length of 1028.2 m and consists of two structurally independent decks with 13 spans. The main span consists of two symmetrical prestressed concrete Niagara box girders, varying in depth from 10.93 m at the pier to 2.57 m at the edge. The main span experienced a progressive abnormal deflection up to 200 mm, leading to radical retrofits in 1988 and 2014. They involved, reducing the load by replacing the pavement with a thinner layer of lightweight asphalt and later installing an external post-tensioning system and stiffening diaphragms. Since 2014, two Leica Nova TM50 topographic total stations have been installed on-site; they measure the displacements over time of 72 optical prisms GPR112 installed along the main span and 12 benchmarks in the surrounding area (Figure 2). In addition, a network of PT100 platinum resistance thermometers measure the concrete temperature for the temperature compensation of displacements [9].

The dataset of satellite SAR images includes 62 SAR X-band images acquired from 2016 to 2020 by the COSMO-SkyMed mission in Stripmap HIMAGE mode and granted for this research study by the Italian Space Agency (ASI). This bridge exhibits high displacement gradients, potentially introducing phase ambiguity errors in InSAR measurements. Moreover, since the viaduct lies in deep valley and is surrounded by peaks exceeding 2000 meters, a mountain hides the bridge to satellites moving along the ascending geometry; therefore, our datasets includes only images acquired in descending geometry.

Figure 1: Main span of the Colle Isarco Viaduct.

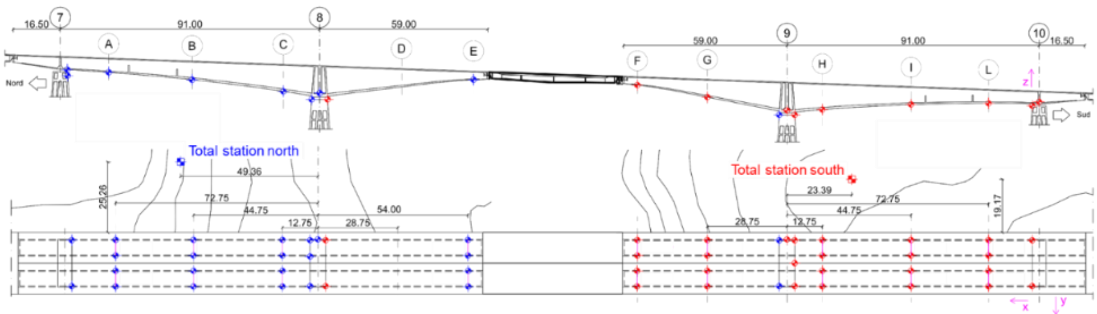

Figure 2: Distribution of the optical prisms along the main span of the Colle Isarco Viaduct.

EXTRACTION OF DISPLACEMENT TIME SERIES

Topographic monitoring provides the displacement time series of the optical prisms located on the viaduct. In our study, we only analyze the displacements of the prisms on the deck. These measurements include the displacements of the deck, the piers, and the ground; they depend on thermal variations, traffic and wind loads, and possible movements of the foundations. Since the piers are over 65 m high and the girder cantilevers are 59 m long, the displacements are mainly due to temperature variation [10]. The vertical component of the displacements reaches (a) daily variations of 1 cm and seasonal variations of 2 cm at the top of the piles, and (b) daily variations of 2 cm and seasonal variations of 4 cm at the end of cantilevers.

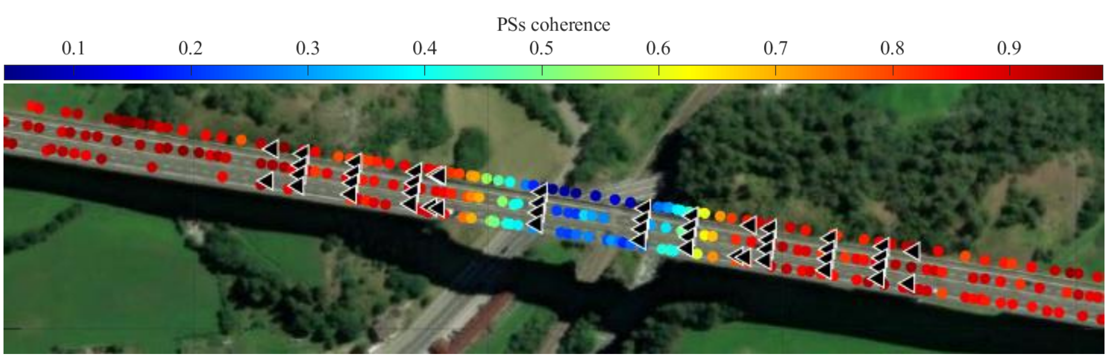

Figure 3: Distribution of optical prisms and PSs over the Colle Isarco Viaduct.

Satellite monitoring provides SAR images, which we analyze through the MT-InSAR technique with the software SARproZ. This technique involves analyzing a series of radar images of the same area taken over several years and comparing their phase differences. Plenty of literature accurately describes this technique in detail [3]–[5], [11]. The location of the bridge makes the analysis of SAR images particularly challenging as mentioned in the previous Section. Despite that, we extracted over 600 PSs along the bridge. However, not all the PSs are characterized by same quality. Indeed, the PSs have different temporal coherence, which indicates the quality of the extracted time series and is a function of the stability of the radar phase measured from PSs over multiple repeat pass radar acquisitions. Figure 3 shows the distribution of the optical prisms installed on the Colle Isarco Viaduct and the PSs extracted over it.

The PSs' colors show that the temporal coherence is smaller over the suspended span that in the other bridge sections. That may be a symptom of the high displacement variation experienced by the bridge's main span, which will be discussed below.

COMPARISON OF DISPLACEMENT TIME SERIES

Based on the coordinates of prisms and extracted PSs, we assigned to each prism the PSs within a 7 m radius. Then, we compared the vertical component of the optical prism displacements measured by the total station with the vertical displacement of the PSs, d_v, calculated as the displacement along the Line of Sight (LoS) d_{LoS} observed by satellites divided by the cosine of the off-nadir angle θ of the satellite LoS [12]:

$$d_v = \frac{d_{LoS}}{\cos(\theta)} \tag{1}$$

Equation (1) assumes that the displacements measured by satellites along the LoS results only from the vertical displacement of the bridge. This assumption is rather strong but plausible since the displacements due to thermal variations are mainly vertical, given the dimensions of piers and spans. Furthermore, the bridge is oriented in a north-south direction, so the satellite cannot measure the displacement components in the longitudinal direction. For each couple of Prism-PS, we used the metrics Root Mean Square Error (σ) and Pearson correlation coefficient (ρ) to quantify the mean error and level of correlation between their displacement time series. Figures 4 and 5 show the direct comparison between prisms and PSs displacement time series performed on two different sections of the Colle Isarco viaduct, which are characterized by different magnitudes of vertical displacements and different temporal coherence of the PSs.

Figure 4 focuses on Section B – the midspan between piles 7 and 8. The displacements of the optical prism measured close to the time the satellite passes over the case study area are highlighted with grey dots and directly compared to the displacements of two PSs identified close to the prism. Those PSs are located at 3.5 and 3.8 m distance from the optical prism and are characterized by a temporal coherence of 0.79 and 0.81; their displacement time series are represented with red and blue lines, respectively. The maximum variation in vertical displacements between two successive satellite acquisitions is approximately 10 mm, which is less than the half of the wavelength of the radar signal (λ/2). Consequently, there is no occurrence of phase ambiguity, which consists of in the inability of SAR to measure displacements greater than λ/2.

Figure 5 focuses on Section E – the bridge section at the end of the cantilever. It is shown the vertical displacement in the case of a PS with a temporal coherence of 0.26, which is lower compared to the PSs in section B. This difference is mainly due to the distinct effect that thermal variation induces in these two positions. Furthermore, measurements at Section E are noisier due to high frequency vertical displacements caused by traffic and wind that sometimes are greater than 20 mm (which is greater than λ/2). In this situation, it was necessary to eliminate the phase ambiguity issue. To achieve this goal, we introduce a novel data fusion approach that utilizes monitoring with optical prisms to fix the displacement acquired from the satellite. Each satellite measurement was corrected by adopting the most accurate replica ±λ/2 which was the closest to the prism measurement at a fixed time interval.

The InSAR vertical displacements are available in general every 16 days around 5:15 p.m. In case of a better temporal coherence 0.79 and 0.81 (section B), σ is 2.39 mm for the first PS and 2.77 mm for the second one, and ρ is 0.85 and 0.80, respectively. In contrast, for a low temporal coherence 0.26 (section E), the overall error is unsatisfactory due to the phase ambiguity: σ = 6.43 mm and ρ = 0.00. After resolving this problem by performing the method above explained, the error improved significantly: σ = 3.08 mm and ρ = 0.88. These results are quite satisfactory and closer to what observed in PSs with temporal coherence >0.7 than before.

This data fusion method requires on-site monitoring and cannot be applied to structures monitored only by InSAR. However, we do that because our aim now is to compare displacement time series measured through a topographic system and satellite InSAR purged from the phase ambiguity, regardless of the method used for solving the phase ambiguity.

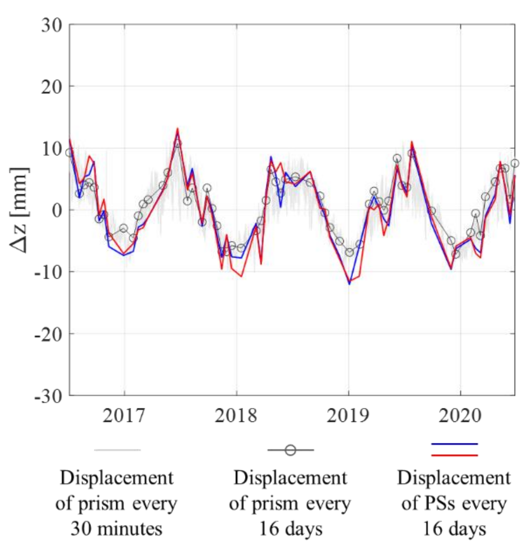

Figure 4: Section B (see Figure 2): vertical displacement of optical prism and PSs

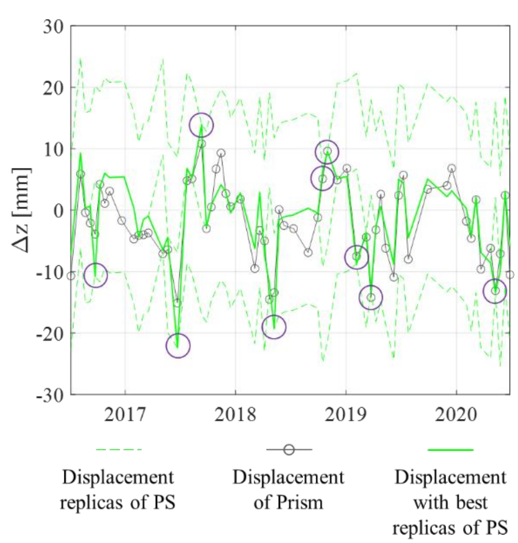

Figure 5: Section E (see Figure 2): vertical displacement of optical prism and PSs

COMPARISON OF LONGITUDINAL DEFORMED SHAPES

The direct comparison between the displacement time series of prisms and PSs may be affected by 3 further issues:

- PS and prisms may not perfectly correspond in terms of position. Some differences in the time series may be due to different displacements that different bridge sections can experience in response to loads.
- Total station measurements and satellite passes are not temporally synchronized. Some differences in the time series may be due to displacements experienced by the structure while the two acquisitions occur.
- Both measurements are subjected to random error, which adds to the other two sources of errors.

To limit these issues and compare time series in the same location on the deck, we performed a least square fitting of the longitudinal deformations of the bridge obtained through the displacements measured with the different technologies, both considering and not considering replicas. We used a third order polynomial for both the right and left girders. The deformation of the suspended span is just a line connecting the positions of the two shear keys which support it. For example, Figure 6 shows the longitudinal deformed shapes of the Colle Isarco Viaduct main spans obtained from the polynomial fitting of displacements measured on 24 July 2017.

Then, we calculated the displacement time series from the sequence of fitted deformed shapes in each bridge section equipped with optical prisms. Figure 7 reports the results for Sections B and E, respectively. A significant improvement is visible, especially in Section E. The metrics result in $\sigma = 2.95$ mm and $\rho = 0.95$ for Section B and $\sigma = 3.16$ mm and $\rho = 0.92$ for Section E in the case considering replicas.

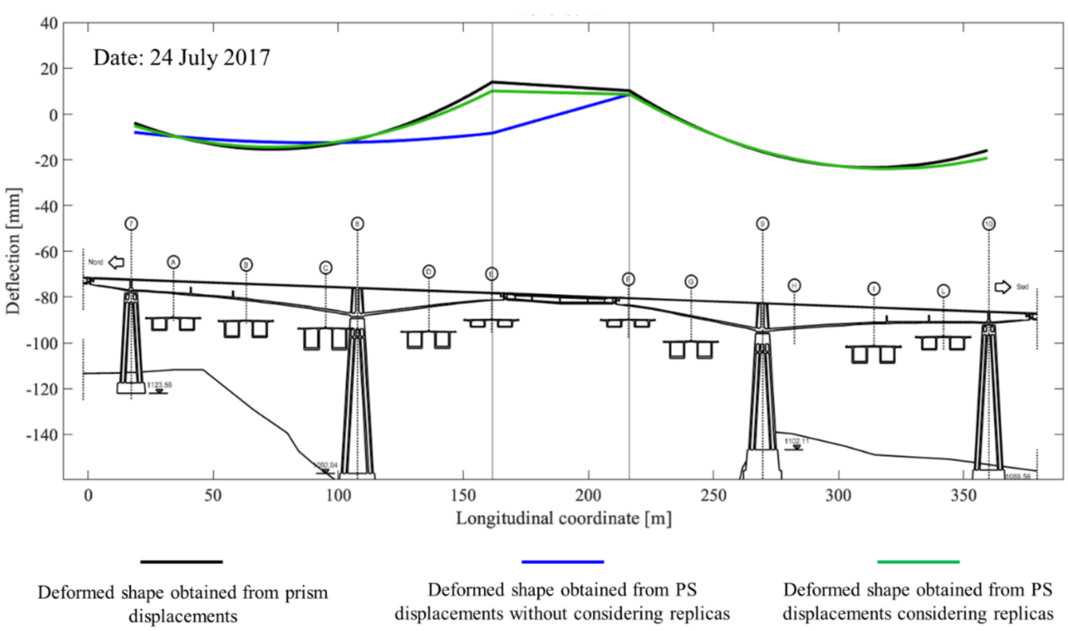

Figure 6: Longitudinal deformed shapes of the Colle Isarco Viaduct main spans obtained from the polynomial fitting of displacements measured on 24 July 2017.

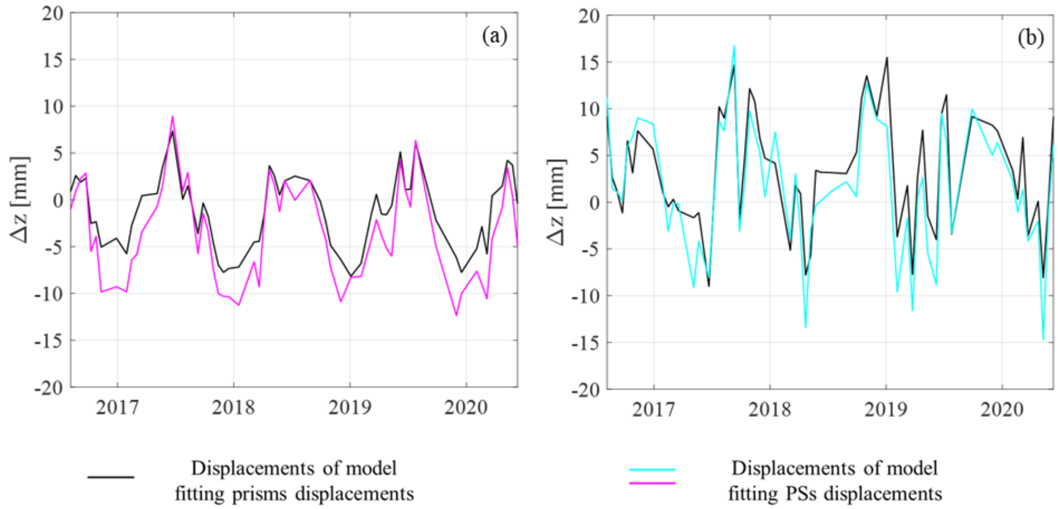

Figure 7: Vertical displacements extracted from the sequence of longitudinal deformed shapes of (a) Section B, and (b) Section E.

CONCLUSIONS

In conclusion, this study demonstrates the potential of Satellite Interferometric Synthetic Aperture Radar (InSAR) for Structural Health Monitoring (SHM) of bridges. By analyzing the displacement time series extracted from 62 COSMO-SkyMed SAR images of the Colle Isarco Viaduct, we have identified several important findings and considerations.

Firstly, we have highlighted the challenges associated with monitoring bridges using InSAR. The presence of long spans and high piers introduces limitations in accurately measuring displacements higher than half the wavelength ($\lambda/2$) of the radar signal due to phase ambiguity. However, we have shown that these limitations can be mitigated by considering replicas or fitting the longitudinal deformed shape of the bridge with a kinematic model.

By quantifying the uncertainties in the displacement time series extracted with the Multi-Temporal InSAR (MT-InSAR) technique, we have provided valuable insights into the reliability of the results. The comparison between on-site and remote technologies reveals that the vertical displacements between two satellite passes, where they are below $\lambda/2$, exhibit a root mean square error (σ) ranging from 2.39 to 2.77 mm and a linear correlation (ρ) of 0.80 to 0.85. In contrast, for vertical displacements exceeding $\lambda/2$, the uncertainty increases to $\sigma = 6.43$ - 10.2 mm and $\rho = 0.00$.

To reduce these uncertainties, we have demonstrated that considering replicas of the original time series extracted with InSAR can improve the results, leading to a decrease in σ to 3.08 - 4.58 mm and an increase in ρ to 0.79 - 0.89. Furthermore, fitting the longitudinal deformed shape of the bridge with a kinematic model allows for additional reduction in uncertainty, resulting in σ values of 2.80 - 3.16 mm and ρ values of 0.92 - 0.93.

In summary, this study demonstrates the feasibility of using Satellite InSAR-based SHM for monitoring bridge. It provides insights into the limitations and uncertainties associated with this approach and offers potential solutions for improving accuracy and reliability. Further research is warranted to explore automated methods for replica selection and to validate these results across a broader range of bridge structures and environmental conditions.

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