SYNTHETIC APERTURE RADAR INTERFEROMETRY FOR STRUCTURAL HEALTH MONITORING OF BRIDGES: POTENTIALITIES AND OPEN RESEARCH QUESTIONS

MARIA PINA LIMONGELLI* AND PIER FRANCESCO GIORDANO†

* Department of Architecture, Built environment and Construction engineering (DABC)
Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20133 Milan, Italy; Lisa Meitner Guest professor at Lund University Faculty of Engineering, Division of Structural Engineering. John Ericssons väg 1. SE-221 00 Lund, Sweden
e-mail: mariagiuseppina.limongelli@polimi.it

† Department of Architecture, Built environment and Construction engineering (DABC)
Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20133 Milan, Italy

Key words: Satellite monitoring, Structural Health Monitoring, InSAR, European Ground Motion Service, COSMO-SkyMed, Sentinel-1, Environmental effect, Civil structure, Bridge.

Abstract. The development of synthetic aperture radar (SAR) interferometry has provided unprecedented opportunities to remotely analyze the behavior of civil structures, transcending traditional limitations associated with in-situ methods. However, while the effectiveness of SAR technology in monitoring wide-area geohazards is demonstrated in several applications, its extension to civil structures, which have a much smaller footprint, requires further investigation of several aspects. This paper investigates the potentialities and challenges connected with the use of SAR technology for civil engineering artifacts, fostered by the availability of remote satellite open data. Recently, the European Space Agency has introduced the European Ground Motion Service (EGMS) under the Copernicus program. This innovative and freely accessible resource provides comprehensive information regarding ground motion across Europe through multitemporal interferometric analysis of Sentinel-1 images acquired since 2015. In this paper the focus is on the Palatino Bridge in Rome, Italy. Data from the ascending and descending orbit are combined to obtain vertical and longitudinal displacements of the structure, allowing for a better estimation of the bridge's response to varying environmental conditions. Results are then compared with those obtained processing high resolution data from COSMO-SkyMed of the Italian Space Agency, showing the consistency of findings.

1 INTRODUCTION

The field of Synthetic Aperture Radar Interferometry (InSAR) has witnessed significant advancements, establishing itself as a prominent monitoring technology in various geoscience domains. With the enhancements in the spatial and temporal resolution of Synthetic Aperture Radar (SAR) images and the evolution of InSAR algorithms, this remote sensing technique has become increasingly applicable to monitor man-made structures, including bridges [1–3]. In comparison to traditional in-situ displacement measurement methods involving inclinometers, extensometers, and Global Navigation Satellite System (GNSS) receivers, InSAR offers several advantages. A primary benefit is the independence from the presence of in-situ monitoring systems thus avoiding the challenges associated with their installation and maintenance. They allow for investigating large areas, and to collect data in any light and environmental conditions. Moreover, the historical behaviour of a bridge can be explored, offering insights into its past and current state. This capability facilitates the tracking of structural anomalies, potentially enhancing the understanding of specific deterioration phenomena or causes of collapse [4].

Furthermore, the higher temporal resolution enabled by the increasing number of satellites and by the reduction of their revisit period, raises the potential effectiveness of SAR data as decision support tools for infrastructure management. However, despite its merits, limitations in the context of civil infrastructure monitoring exist, especially associated with the interpretation of InSAR outcome [5]. The spatial resolution of data is still low, even for high resolution data, to enable the use of data without employing averaging or interpolation techniques which inevitable add uncertainty.

A National research project titled “Structural Health Monitoring and Satellite Data.” And funded by ReLUIS [6] started in 2019 to investigate the potentialities and delve into the possible obstacles related to the use of SAR images for civil structures. The project led to the publication of the National Guidelines that are currently under public review [7]. The document describes the fundamentals of the technology and presents a number of case studies relevant to several types of structures. One of these is focused on the study of the displacements of the Palatino Bridge in Rome, retrieved from high resolution COSMO-SkyMed (CSK) provided by the Italian Space Agency and processed by CNR-IREA.

However, the use of high-resolution images often necessitates costly InSAR software and the investment of time and resources in developing the necessary processing skills. These requirements frequently serve as primary obstacles for civil engineers contemplating the adoption of InSAR for monitoring civil infrastructures.

Recently, the European Space Agency (ESA) offered the European Ground Motion Service (EGMS) under the Copernicus program [8]. The EGMS is a service utilizing InSAR technology to monitor ground deformations across Europe. EGMS processes full-resolution data from Sentinel-1 satellites, employing advanced InSAR techniques along with GNSS calibration. The system, operational since 2022, delivers user-friendly services accessible through a dedicated portal, offering different products. EGMS utilizes Sentinel-1 Interferometric Wide Swath (IWS) data collected starting from February 2015, with annual updates.

In this paper, the potential of EGMS technology in monitoring the structural behaviour of civil infrastructure is explored through a comparative analysis with the CSK data, with a specific focus on the Palatino Bridge. By using EGMS data from the ascending and the descending orbit, the component of the displacement along the vertical and the longitudinal direction of the bridge are estimated.

This paper is organized as follows. Section 2 offers an overview of InSAR technology, providing foundational information on its principles and applications. Section 3 describes the case study, i.e., the Palatino Bridge in Rome, Italy. Sections 4 and 5 detail the satellite data processing methodologies employed in this study based on EGMS and SCK data, respectively. Finally, Section 6 presents the main findings and conclusions drawn from the analysis of the structural behaviour of the Palatino Bridge, accompanied by considerations for future work.

2 INSAR FUNDAMENTALS

The fundamental principle of InSAR consists in utilizing phase differences, called interferograms, between two temporally distinct SAR (Synthetic Aperture Radar) images [9]. Interferogram generation involves image pairs acquired from closely situated tracks on the same orbit, with the spatial separation termed as baseline, aiming to reduce both spatial decorrelation and topography errors. This comparison aims to deduce positional variations (displacement) occurring between the two acquisition epochs. The revisit time of satellites used for InSAR applications is typically on the order of weeks.

Displacement measurements are made along the Line of Sight (LOS) from the sensor to the measurement point. SAR satellites primarily operate in a polar orbit, covering both North and South poles, with two acquisition modes: (i) ascending mode (south to north trajectory) and (ii) descending mode (north to south trajectory). InSAR outcomes include displacement maps, velocity maps, and time series of displacements, applicable at both regional and local scales. Persistent Scatterers (PS) and Distributed Scatterers (DS) exhibit minimal noise and maintain a consistent reflection throughout the observation period. PS are characterized by a dominant response from a robust reflecting object, showcasing stability over time. In contrast, DS are linked to varied responses arising from different small scattering objects.

Throughout the paper, the term PS is employed to encompass both Permanent Scatterers and Distributed Scatterers. Coherence, indicating the phase preservation correlation between the signals of two SAR acquisitions, is a crucial metric ranging from 0 (indicating complete noise interferogram) to 1 (representing a flawless interferogram with no noise). Nonetheless, monitoring structural displacement along the LOS is influenced by satellite acquisition geometry and the object's position. The object's geometry plays a crucial role, and certain displacements may be challenging to measure. Specifically, measuring displacements along the North-South direction proves challenging, while displacements in the East-West direction are typically more accurately captured.

In this study, two types of InSAR displacement data are employed: EGMS data based on Sentinel-1 images and data provided by CNR-IREA based on CSK images.

Launched in 2014, the Sentinel-1 (S1) satellite mission was specifically crafted to systematically capture interferometric C-band SAR image stacks, offering a temporal resolution of 6 days and a spatial resolution around 10 meters. The EGMS employ both PS and DS InSAR processing techniques. In this study, Level 2b (L2b) data EGMS data are utilized. L2b data undergo calibration with a GNSS reference network. This operation ensures that measurements are referenced to a standardized frame rather than a specific reference point.

The analysis of CSK data was conducted by CNR-IREA, and the obtained results have been shared in the context of the WP6-2019-21 ReLUIS Project titled “Structural Health Monitoring and Satellite Data.” CSK data were acquired between July 2011 and March 2019, specifically in the StripMAP HIMAGE mode with a 3-meter spatial resolution, were processed by CNR-IREA using the Differential Interferometric Synthetic Aperture Radar (DInSAR) technique known as the "Parallel SBAS Interferometry Chain". [10] The DInSAR techniques is also taking into consideration both PSs and DSs.

3 CASE STUDY

The case study is the Palatino Bridge spanning the Tiber River in Rome, Italy, shown in

Figure 1. Constructed in the second half of the 19th century near the remains of a Roman bridge, this structure is a continuous iron truss, 155 meters long and 20 meters wide. It is supported by masonry structures, including four piers and two abutments, with foundations in the water. The piers have different angles relative to the deck's axis. The deck is anchored to a central pier and supported by cylindrical roller bearings on the other piers. Two joints connect the deck to the abutments. This case study was investigated in previous studies [11, 12].

Figure 1: Palatino Bridge, Italy: (a) Southside of the bridge; (b) Truss beams of the deck.

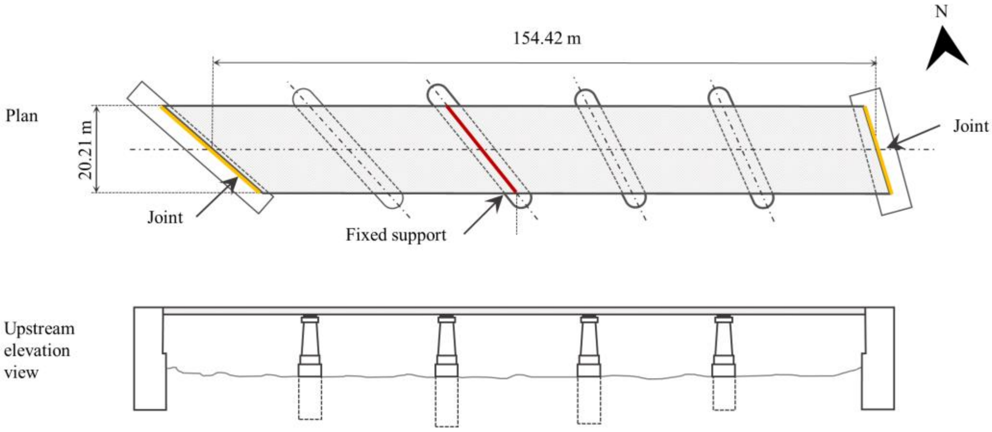

Figure 2: Palatino Bridge, Italy: Plan and elevation.

4 EGMS DATA PROCESSING AND RESULTS

The EGMS data used in this study include the ascending dataset denoted as EGMS_L2b_022_0827_IW3_VV and the descending dataset labelled as EGMS_L2b_117_0247_IW2_VV. Data have been integrated into a Geographic Information System (GIS) software, allowing for the visualization of PS on the Earth's surface. Figure 3 displays the PS located in the area surrounding the Palatino Bridge extracted from the EGMS datasets. The colors of the PS relate to their mean velocity in the observation period. Notably, PS associated with the ascending orbit predominantly exhibit positive displacements, signifying movement toward the satellite. Instead, PS from the descending orbit showcase negative velocities, indicating that these PS are moving away from the satellite, compatible with local subsidence.

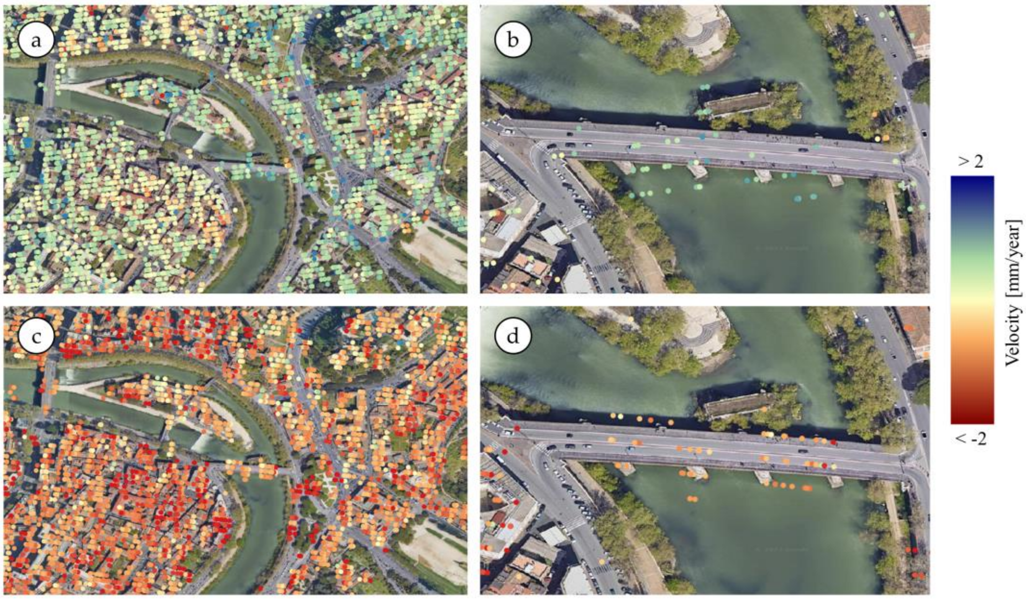

Figure 3: PS on the bridge and surrounding areas: (a) and (b) ascending orbit; (c) and (d) descending orbit.

Determining the precise positions of each PS on the structures poses a significant challenge. To overcome this, a clustering strategy has been implemented, based on the similarity of time histories. The coefficient of correlation between pairs of time series is used as a measure of similarity. A coefficient of correlation equal to 1 and -1 indicates perfect positive and negative linear correlation, respectively, between two time series. Values close to 0 denote no correlation. By plotting the correlation matrix for ascending and descending orbits and excluding PS with correlations close to 0, a distinct clustering pattern emerges, see Figure 4.

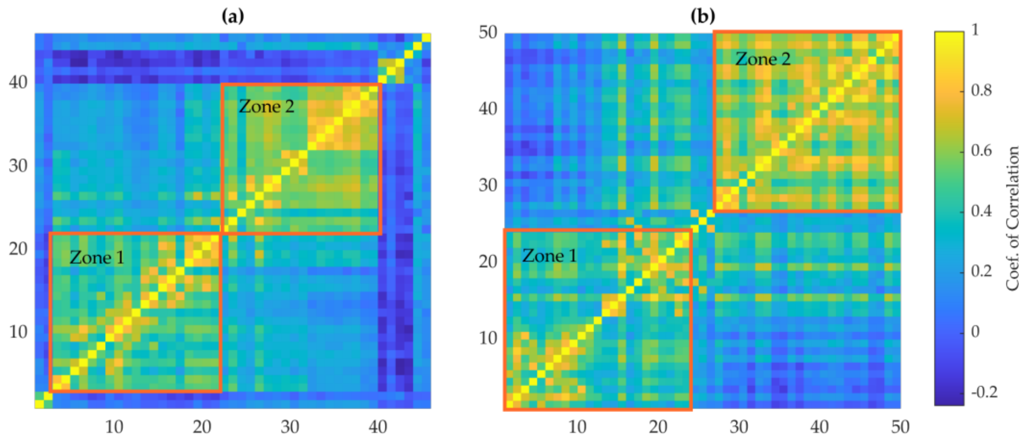

Figure 4: Correlation matrix between the displacement time series of the PS from the (a) ascending and the (b) descending orbit.

The PS form two distinct groups corresponding to the West and East zones of the bridge, called Zone 1 and Zone 2, respectively. The values on the matrix axes in Figure 3 indicate the PS order concerning their longitude, arranged from low to high. The clustered PS are represented in Figure 5. Figure 6 shows the mean LOS displacements of the PS from the two areas and orbits.

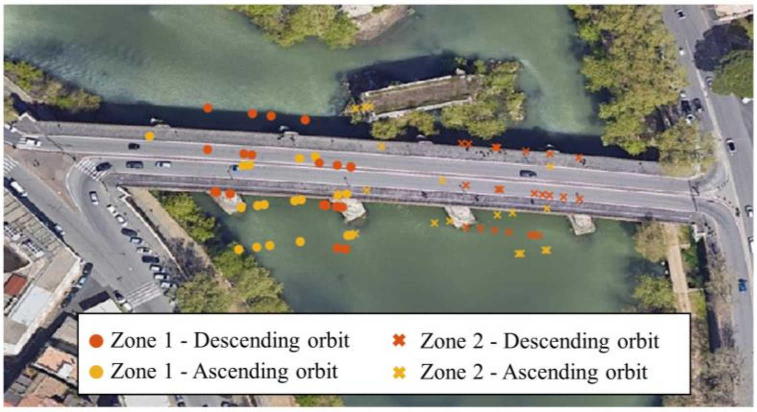

Figure 5: Clusters of PS on the bridge.

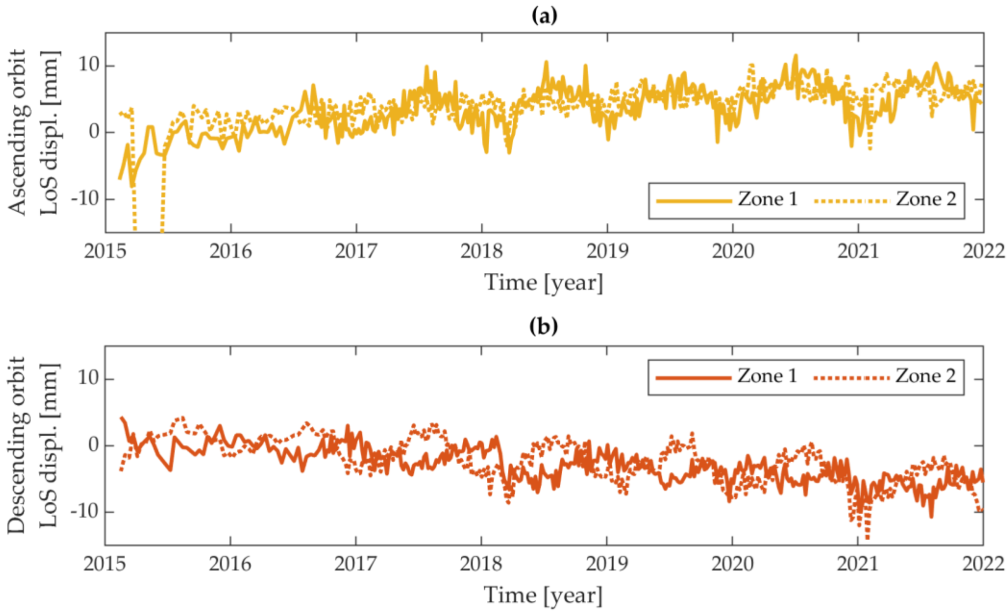

Figure 6: Mean displacement time series of the PS from the (a) ascending and the (b) descending orbit.

To generate the time series plots, a normalization process has been applied by subtracting the mean LOS displacement over the initial two years, assumed as reference period in which the structure is in healthy conditions. By centring the data around a common reference point, the resulting plots allow for a focused analysis of the relative movements and patterns in the displacement time series facilitating a more straightforward comparison of results. The displacement time history in Figure 6(a) exhibits a positive trend for the ascending orbit; a negative trend for the descending one is observed in Figure 6 (b). In each subplot, the two zones display opposing seasonal patterns.

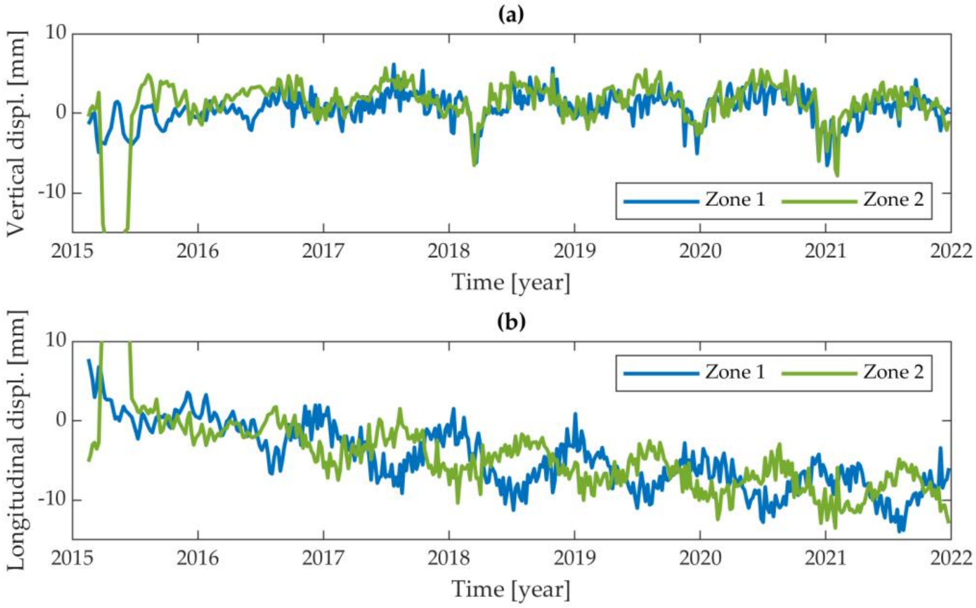

Figure 7: Time series of (a) vertical and the (b) longitudinal displacement.

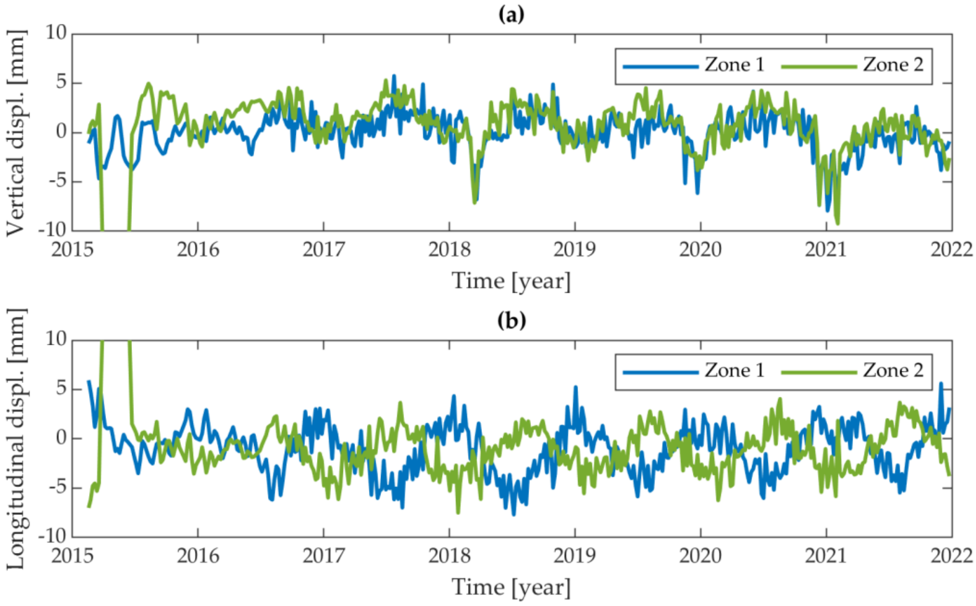

Figure 8: Time series of (a) vertical and the (b) longitudinal displacement after removing generalized trends.

To understand the bridge's behaviour, it is crucial to determine the vertical and longitudinal (West-East) components of displacements. This involves establishing temporal consistency between the ascending and descending datasets, which were acquired at different days. To achieve this, a linear interpolation is applied to the ascending and descending time histories across the entire range of acquisition times. Following this, the estimation of displacements in the vertical and longitudinal directions is performed according to the equations in reference [11]. This estimation is based on a few assumptions: (i) the vertical direction of the geoid aligns with the ellipsoid, (ii) the Azimuth Look Direction of the satellite orbit aligns with the North-South direction, and (iii) the structure is assumed to be on a flat surface. The resulting real components of the displacement are displayed in Figure 7.

In 2015, the displacements exhibit anomalies that are likely unrelated to the structural condition of the bridge but may be attributed to variations in the quality of satellite data. Both the vertical and longitudinal displacements exhibit a seasonal trend attributed to temperature variations across different seasons. In terms of vertical displacements, both areas demonstrate a similar behavior. Conversely, concerning longitudinal displacements, the two areas display opposite trends, consistently with the positioning of the fixed connection between the deck and the masonry support. Also, the velocity of longitudinal displacement appears to increase over time, a phenomenon that lacks a plausible physical explanation.

Instead, this trend is likely attributed to the overall positive velocities indicated by the ascending data, suggesting soil uplift, see Figure 3(a) and (b). Given that subsidence is a common occurrence in Rome [13], it raises the possibility of a potential issue with the EGMS ascending dataset. To mitigate the influence of the observed general trend, unrelated to structural conditions, an examination of the PS in the vicinity of the bridge is undertaken, particularly those situated near the Tiberine island adjacent to the bridge. The mean velocity of these PS is determined as the slope of the best-fitting line across all displacement time histories. This velocity is then employed to calculate the displacement to be subtracted from the time histories of the actual displacement components of the Palatino Bridge. This is done for data from both orbits. The resultant displacement time series, purged of the generalized displacement trends, is presented in Figure 8. Vertical displacements exhibit no significant change. Furthermore, longitudinal displacements no longer display a significant negative velocity.

5 CSK DATA PROCESSING AND RESULTS

The results derived from the analysis of EGMS data are compared with those obtained through the processing of high-resolution CSK data.

Figure 9: PS from the (a) ascending and (b) descending datasets.

In this case, the position of the extracted PS is influenced by minor uncertainties. Additionally, the increased spatial resolution characterizing the CSK data contributes to a higher number of identified PS.

A GIS software is used to display the PS obtained through the DInSAR analysis. Figure 9 shows

PSs on the bridge deck from both ascending and descending orbits. Most PS exhibit zero velocity over the observation period, depicted by a light-yellow color. Also, they are almost uniformly distributed along the bridge deck.

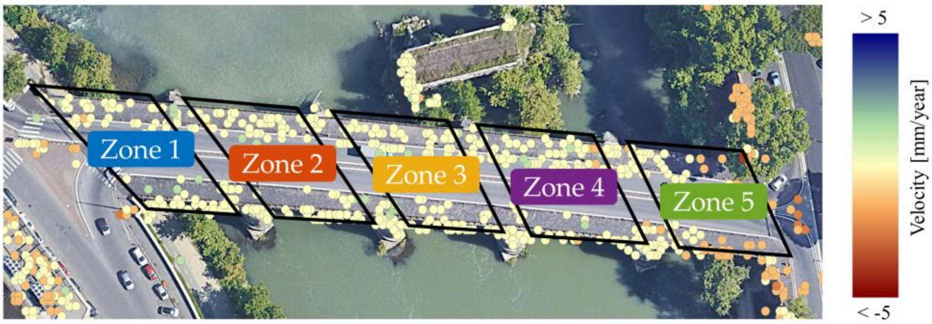

Figure 10: Clustering of PS obtained from CSK data from the ascending and the descending orbit.

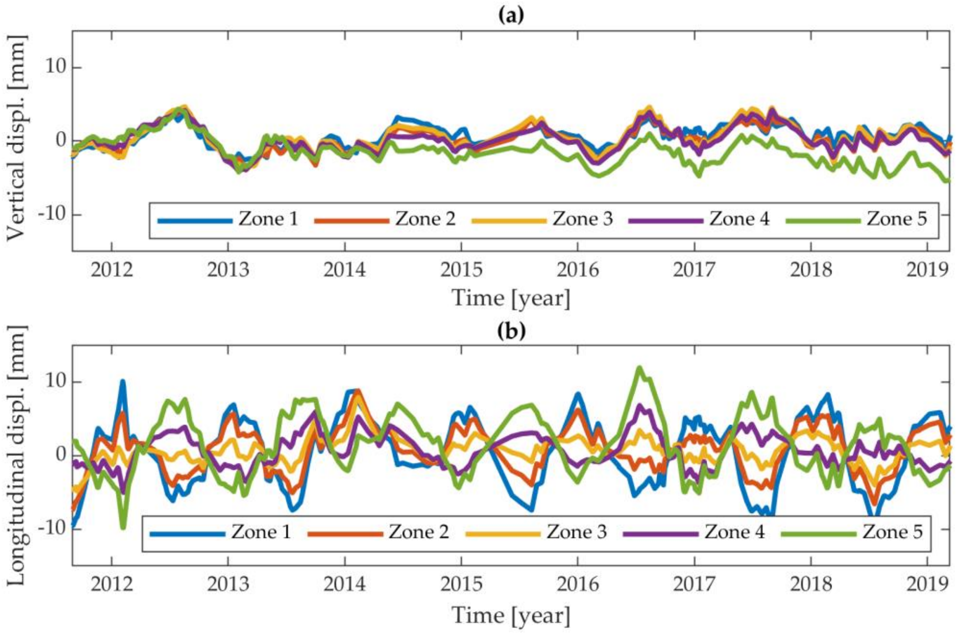

Figure 11: Time series of (a) vertical and the (b) longitudinal displacement using CSK data (five areas).

The SAR satellite data analysis encompasses several key steps. First, PS are grouped into five "reference areas," each corresponding to deck segments between supports, see Figure 10. PS near piers are excluded due to challenges in attribution to the deck or piers. Also, PS with average speeds beyond ±2σ (σ=standard deviation of average speed within each area) during the training period are treated as outliers and excluded.

Then, the mean displacement of time history is computed for each area and satellite orbit. For each time history, the mean displacement in the initial two years is subtracted from subsequent displacement observations, ensuring displacement oscillate around zero. Ascending and descending time histories are interpolated across the entire acquisition timeline to combine datasets acquired at different times. Finally, vertical and longitudinal displacements are estimated using the equations in reference [7]. Figure 11 presents the time series of vertical and longitudinal displacements for the five zones.

Figure 12: Clustering of PS obtained from CSK data from the ascending and the descending orbit.

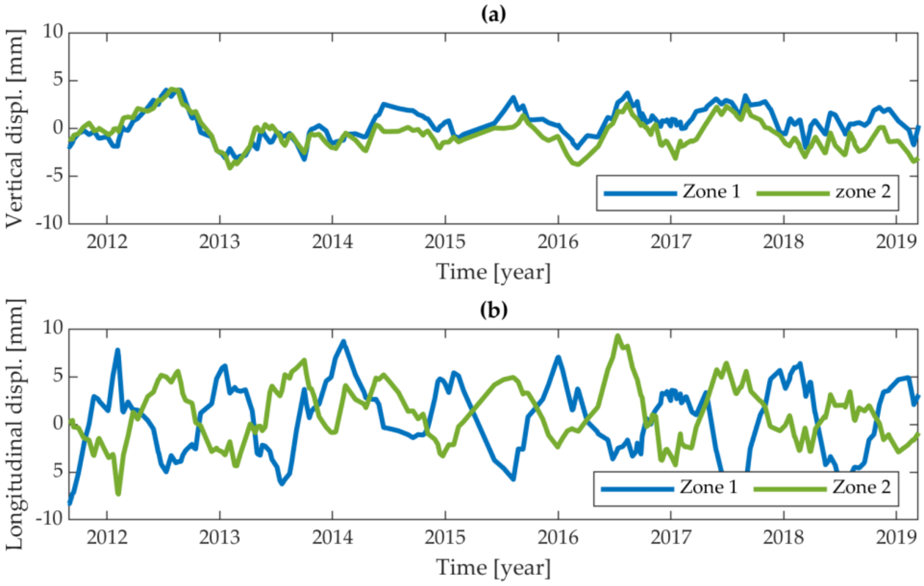

Figure 13: Time series of (a) vertical and the (b) longitudinal displacement using CSK data (two areas).

Vertical displacements exhibit irregular behavior over time, yet all areas demonstrate a consistent pattern, except for Zone 5 (green line) with steadily decreasing displacements. Longitudinal displacements display a seasonal trend, peaking in summer and minimizing in winter. Zone 3 maintains close-to-zero longitudinal displacements, potentially attributed to a malfunction in the cylindrical roller between Decks 3 and 4. The longitudinal behavior of the five areas remains consistent over time.

For the purpose of facilitating a comparison of results, this study narrows its focus to two specific areas, as shown in Figure 12. The new Zone 1 comprises PS from the former Zones 1 and 2, while the new Zone 2 consists of PSs from the former Zones 4 and 5. Following the outlined procedure, CSK data from the two orbits are processed to extract the vertical and longitudinal components of displacements in the two bridge segments. Results are displayed in

Figure 13. The results are very similar to those shown in Figure 8 both in term of trend and magnitude of displacements.

6 MAIN FINDINGS AND CONCLUSION

This study has utilized L2b data from the EGMS to conduct a comprehensive examination of the behavior of the Palatino Bridge, a metal structure located in Rome, Italy. The EGMS dataset, encompassing calibrated information from both ascending and descending orbits, enabled a detailed analysis of the bridge's displacement over time. The focus on PS data, coupled with a clustering strategy based on time-history similarities, revealed distinct patterns in PS behavior, particularly clustering in two main zones corresponding to the East and West sections of the bridge. Subsequent removal of general trends, not necessarily indicative of structural conditions, allowed for a better understanding of the bridge's displacement characteristics. To strengthen the study, a comparative analysis with high-resolution CSK data was undertaken demonstrating the consistency of results.

The results underscore the effectiveness of EGMS data in capturing the temporal and spatial behavior of the case study. The identified seasonal trends in vertical and longitudinal displacements offer insights into the structural response to changing environmental conditions. Nevertheless, the anomalies observed in longitudinal displacements emphasize the necessity of cautious data interpretation.

In addition to its current applications, InSAR technology holds immense potential for further advancements in civil infrastructure monitoring. The scalability and remote sensing capabilities of InSAR offer a promising avenue for large-scale infrastructure management. Future research should explore the full potential of InSAR in enhancing our understanding of structural behavior, enabling more proactive and effective maintenance strategies.

Open research questions include the development of automated and efficient data processing techniques. Moreover, addressing the limitations associated with spatial resolution remains a crucial challenge. Investigating ways to improve the interpretability of InSAR outcomes for complex structures and developing standardized procedures for data interpretation are also vital areas for future exploration.

The integration of InSAR data with information from in-situ monitoring systems holds promise for a comprehensive understanding of civil infrastructure behavior. The fusion of these datasets could provide a synergistic approach, combining the broad spatial coverage of InSAR with the detailed and localized insights offered by in-situ measurements. This approach may enhance the accuracy and reliability of structural assessments, paving the way for more robust infrastructure monitoring strategies.

ACKNOWLEDGMENT

This publication has been prepared using European Union's Copernicus Land Monitoring Service information; https://doi.org/10.2909/d92e61be-d6e8-4bc1-aa10-f742bf27bab9. CNR-IREA is gratefully acknowledged for processing and providing DInSAR derived data. This study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005). This study was partially funded by the Lombardy Region and by the Italian Civil Protection Department within the project RELUIS 2022–2024 WP6 “Structural Health Monitoring and Satellite Data”.

REFERENCES

1. Tonelli, D., Caspani, V.F., Valentini, A., Rocca, A., Torboli, R., Vitti, A., Perissin, D., Zonta, D.: Interpretation of Bridge Health Monitoring Data from Satellite InSAR Technology. Remote Sens. 15, 5242 (2023). https://doi.org/10.3390/rs15215242.
2. Talledo, D.A., Miano, A., Bonano, M., Di Carlo, F., Lanari, R., Manunta, M., Meda, A., Mele, A., Prota, A., Saetta, A., Stella, A.: Satellite radar interferometry: Potential and limitations for structural assessment and monitoring. J. Build. Eng. 46, 103756 (2022). https://doi.org/10.1016/j.jobe.2021.103756.
3. Farneti, E., Cavalagli, N., Venanzi, I., Salvatore, W., Ubertini, F.: Residual service life prediction for bridges undergoing slow landslide-induced movements combining satellite radar interferometry and numerical collapse simulation. Eng. Struct. 293, 116628 (2023). https://doi.org/10.1016/j.engstruct.2023.116628.
4. Sousa, J.J., Bastos, L.: Multi-temporal SAR interferometry reveals acceleration of bridge sinking before collapse. Nat. Hazards Earth Syst. Sci. 13, 659–667 (2013). https://doi.org/10.5194/nhess-13-659-2013.
5. Macchiarulo, V., Milillo, P., Blenkinsopp, C., Reale, C., Giardina, G.: Multi-temporal InSAR for transport infrastructure monitoring: recent trends and challenges. Proc. Inst. Civ. Eng. - Bridg. Eng. 176, 92–117 (2023). https://doi.org/10.1680/jbren.21.00039.
6. ReLUIS: Project ReLUIS-DPC 2019-2021, https://www.reluis.it/it/progetti-dpc-reluis/dpc-reluis-2019-2021.html, last accessed 2023/11/20.
7. ReLUIS: Guidelines, https://www.reluis.it/images/stories/Linee Guida Satellitari-capitoli 1-4 BOZZA.pdf, last accessed 2023/11/20.
8. Costantini, M., Minati, F., Trillo, F., Ferretti, A., Novali, F., Passera, E., Dehls, J., Larsen, Y., Marinkovic, P., Eineder, M., Brcic, R., Siegmund, R., Kotzerke, P., Probeck, M., Kenyeres, A., Proietti, S., Solari, L., Andersen, H.S.: European Ground Motion Service (EGMS). In: 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS. pp. 3293–3296. IEEE (2021). https://doi.org/10.1109/IGARSS47720.2021.9553562.
9. Ferretti, A., Prati, C., Rocca, F.: Permanent scatterers in SAR interferometry. IEEE Trans. Geosci. Remote Sens. (2001). https://doi.org/10.1109/36.898661.
10. Manunta, M., De Luca, C., Zinno, I., Casu, F., Manzo, M., Bonano, M., Fusco, A., Pepe, A., Onorato, G., Berardino, P., De Martino, P., Lanari, R.: The Parallel SBAS Approach for Sentinel-1 Interferometric Wide Swath Deformation Time-Series Generation: Algorithm Description and Products Quality Assessment. IEEE Trans. Geosci. Remote Sens. (2019). https://doi.org/10.1109/TGRS.2019.2904912.
11. Giordano, P., Turksezer, Z., Previtali, M., Limongelli, M.: Damage detection on a historic iron bridge using satellite DInSAR data. Struct. Heal. Monit. 21, 2291–2311 (2022). https://doi.org/10.1177/14759217211054350.
12. Giordano, P.F., Previtali, M., Limongelli, M.P.: Monitoring of a Metal Bridge Using DInSAR Data. In: Rizzo, P. and Milazzo, A. (eds.) European Workshop on Structural Health Monitoring. EWSHM 2022. Lecture Notes in Civil Engineering. pp. 397–406. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-07258-1_41.
13. Stramondo, S., Bozzano, F., Marra, F., Wegmuller, U., Cinti, F.R., Moro, M., Saroli, M.: Subsidence induced by urbanisation in the city of Rome detected by advanced InSAR technique and geotechnical investigations. Remote Sens. Environ. (2008). https://doi.org/10.1016/j.rse.2008.03.008.