

# **Spaceborne Interferometry for Bridge Monitoring: Advancing Structural Integrity Management Through Remote Sensing**

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## **ABSTRACT**

Bridges are essential components of civil infrastructure, and ensuring their structural integrity is crucial for public safety and service continuity. Recent advancements in Synthetic Aperture Radar Interferometry (InSAR) have significantly enhanced our ability to remotely monitor structural behavior, offering a valuable complement to traditional inspection and sensor-based methods. The recently published Italian guidelines for InSAR monitoring of civil structures, developed under a project funded by the Italian Civil Protection, provide essential standards and best practices for integrating InSAR into infrastructure management. The European Ground Motion Service, part of the Copernicus program, provides valuable ground motion data across Europe using Sentinel-1 imagery. In addition to routine monitoring, InSAR holds substantial promise for post-event forensic analysis. It can help engineers investigate the underlying causes of bridge failures by revealing patterns of progressive displacement leading to collapse, critical information that traditional inspection and monitoring methods often miss. This keynote explores the use of spaceborne InSAR for structural health monitoring of bridges, focusing on InSAR data clustering for the interpretation of bridge behaviour, and collapse investigation.

## **INSAR MONITORING OF CIVIL STRUCTURES**

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technology that uses radar signals backscattered by the Earth's surface over time to measure ground surface deformation. The backscattered signals are processed into grayscale digital images, commonly known as SAR images. Each pixel in these images contains amplitude and phase data: the amplitude reflects the strength of the returned signal, indicating how much of the emitted wave was reflected toward the sensor, while the phase corresponds to the total distance the signal traveled to and from the target. By comparing the phase differences between two images of the same area, acquired at different times, InSAR can detect movements of the Earth's surface or displacements of

structures, such as bridges, due, for example, to settlements, subsidence phenomena, or landslides. InSAR processing techniques provide the temporal evolution of point-wise displacements on the Earth's surface in the Line of Sight (LOS) direction that connects the point on the Earth's surface to the satellite. To leverage the phase information in SAR data, it is necessary to analyze multiple images of the same location taken at different times. This enables the generation of interferograms - core to Interferometric SAR (InSAR) techniques—which reveal surface displacements with high accuracy. Most of InSAR methods focus on Persistent Scatterers (PSs), which are radar targets exhibiting consistent electromagnetic reflections over time. These PSs are commonly found on artificial structures (e.g., roads, infrastructure, buildings, and landmarks) as well as on naturally stable features. One of the primary benefits of using InSAR for bridge monitoring is its ability to detect millimeter-level displacements over time. This makes it useful for identifying long-term structural issues such as subsidence, settlements, or thermal expansion-related movements. Since the data is acquired from satellites, it allows for the remote monitoring of bridges located in difficult-to-access or hazardous areas - such as those spanning rivers, deep valleys, or urban congestion - without requiring any installation on the structure itself. Furthermore, InSAR's wide-area coverage enables the simultaneous observation of multiple structures within a region, offering a scalable solution for authorities tasked with monitoring large transportation networks. In addition, InSAR benefits from the availability of historical satellite data. This enables retrospective analyses that can reveal how a bridge's behavior has changed over the years. InSAR data is increasingly accessible. Not least, differently from optical satellite data, it can be collected in any light and weather conditions. Such characteristics are particularly valuable for monitoring the structural performance of bridges over time.

In recent years, InSAR monitoring has attracted significant interest from several research groups, establishing itself as a prominent monitoring technology for large-scale phenomena such as ground subsidence in urban or mining areas, tectonic movements or volcanic activity, and glacier flow monitoring. 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 [1–4]. In Italy, in 2019, a research initiative called 'Structural Health Monitoring and Satellite Data' was launched, funded by the Department of Civil Protection in the framework of the research activities of the Interuniversity Consortium ReLUIS (Network of University Laboratories of Seismic and Structural Engineering) and collaboration with the Institute for Electromagnetic Sensing of the Environment (CNR-IREA). The scope of the project was to explore potential applications and limitations of using InSAR monitoring for civil infrastructure. A main deliverable of the project is a document containing the national guidelines for InSAR monitoring [5], which outlines the core principles of SAR technology and includes a series of case studies covering various structural types. Several research groups are working on the application of InSAR monitoring of bridges.

This activity in Europe is facilitated by the availability of open data made available by the European Space Agency on an online platform, in the context of the recently launched European Ground Motion Service (EGMS). This service is a part of the Copernicus program that provides free processed Sentinel-1 Interferometric Wide Swath (IWS) data collected since February 2015. Data collected across Europe are calibrated with GNSS measurements and updated every year.

This paper reports on some recent research activities on the use of InSAR for bridge monitoring, for structural behaviour monitoring, and collapse analysis.

## DATA CLUSTERING FOR STRUCTURAL BEHAVIOUR ANALYSIS

While InSAR monitoring offers several advantages, it also comes with issues stemming from various sources of uncertainty that affect the data. These include the variable availability of measurements on the monitored structure, measurement noise, unmeasured displacement components, or limitations in spatial and temporal resolution. The reliability of InSAR measurement points on a structure is influenced by factors like SAR sensor resolution, geometric distortions, the structure's shape and surface roughness, and the stability of its reflective properties. Atmospheric conditions, especially moisture in humid or water-rich environments, can introduce noise and false displacement signals. Additional limitations arise from spatial and temporal decorrelation, caused by changes in satellite imaging geometry or ground conditions such as vegetation, snow, or urban development. Structural vibrations from traffic or wind can also reduce image coherence, affecting measurement accuracy. All these phenomena can reduce the number of SAR measurement points. For example, Figure 1 shows the distribution of PSs for four datasets retrieved from the EGMS for the Schottwien Viaduct in Austria. The color scale represents the average velocity of displacement along the LOS during the observation period. Positive velocity values (blue color) indicate movement along the LOS towards the satellite, while negative values (red color) indicate movement away from the satellite. A significant number of PSs are present on the viaduct, making it suitable for InSAR monitoring. However, the west portion of the bridge – corresponding to the first span – lacks PSs from the ascending orbit.



Figure 1. Distribution of PSs on the Schottwien Viaduct and the surrounding area.

A further source of uncertainty in InSAR data stems from the relatively low spatial and temporal data resolution. Temporal uncertainty is associated with gaps between acquisitions, dictated by satellite revisit times that can vary from 1 to 46 days depending

on the satellite constellation [6]. Spatial resolution is constrained by the SAR system’s resolution, which depends on antenna size and signal bandwidth. Current systems provide spatial resolution ranging from approximately 0.3 m to 28 m [6]. In Figure 2, the PSs provided on the same bridge by a high (CosmoSkyMED, Band X) and a medium (Sentinel 1, Band C) resolution dataset are compared, highlighting the different number of PSs provided by the two constellations. While these factors may be negligible for monitoring large-scale geophysical phenomena such as landslides or land subsidence, they become critical when monitoring the structural behavior of infrastructures like bridges, where displacements have smaller spatial footprints and may occur over much shorter timescales. Another limitation is the line-of-sight constraint inherent in satellite-based radar imaging. SAR sensors are typically deployed on satellites following near-polar orbits that are slightly tilted relative to Earth’s meridians. These orbital paths are composed of two segments: the ascending pass, moving from the South to the North Pole, and the descending pass, traveling in the opposite direction. Displacements are measured in the direction perpendicular to the orbit. As a result, movements along the North-South direction, which almost coincide with the satellite orbits, may be underestimated or missed entirely by a single SAR acquisition geometry. On the other hand, reconstructing the full three-dimensional displacement vector (e.g., in the longitudinal, transversal, and vertical directions of a bridge’s local reference system) from LOS measurements acquired by different orbits requires data transformation and simplifying assumptions, which introduce additional uncertainties [4]. To overcome these limitations, one widely adopted approach is the combination of ascending and descending orbit datasets obtained over the same area during overlapping timeframes [3] to reconstruct the three-dimensional displacement fields. However, variations in the spatial distribution of PSs between datasets, along with temporal gaps in data acquisition, necessitate the application of resampling techniques before the combination of the two datasets. Temporal resampling is usually performed by linear interpolation to align acquisition times, while spatial resampling methods – such as interpolation, nearest neighbor, or grid-based subsampling – homogenize spatial coverage.

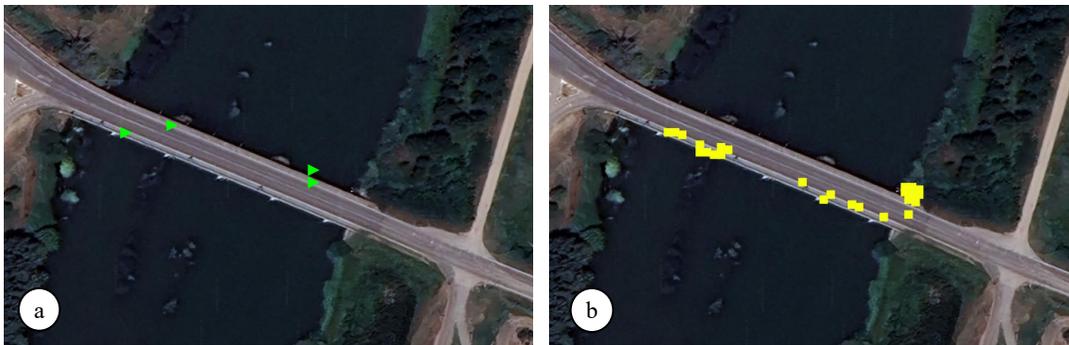


Figure 2. a) Sentinel 1, Band C. b) CosmoSkyMED, Band X.

On one side, resampling reduces uncertainty through the introduction of spatial and temporal continuity conditions; on the other, it introduces approximations that increase uncertainty. Recently, a framework to quantify the effect of resampling of the grid-based approach to resampling was proposed in reference [4]. The uncertainty of resampled data is quantified using a metric defined in terms of the average standard deviation  $\bar{\sigma}_{d_E}$  of the displacement  $d_E$  reconstructed using InSAR data from two orbits, in a certain

direction  $E$ . The average is taken over the length  $T$  of the InSAR dataset and the number  $N$  of areas identified by the considered grid.

$$\bar{\sigma}_{d_E} = \frac{1}{N} \sum_{n=1}^N \frac{1}{T} \sum_{t=1}^T \sigma_{d_{E,n}^t} \quad (1)$$

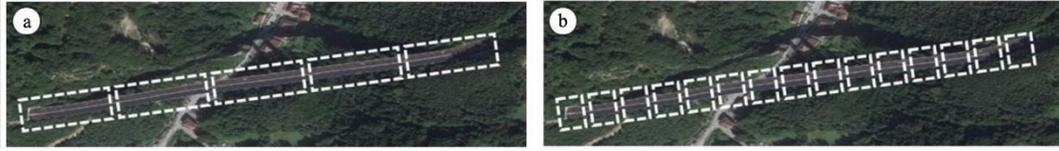


Figure 3. Schottwien Viaduct. Example of a 5-areas grid (b); and a 15-areas grid.

Figure 4 reports the displacement time histories and the relevant confidence intervals considering a 5-area grid and a 15-area grid. The two configurations yield similar mean displacement time series  $d_E$ , whereas the confidence interval significantly decreases as the number of areas increases.

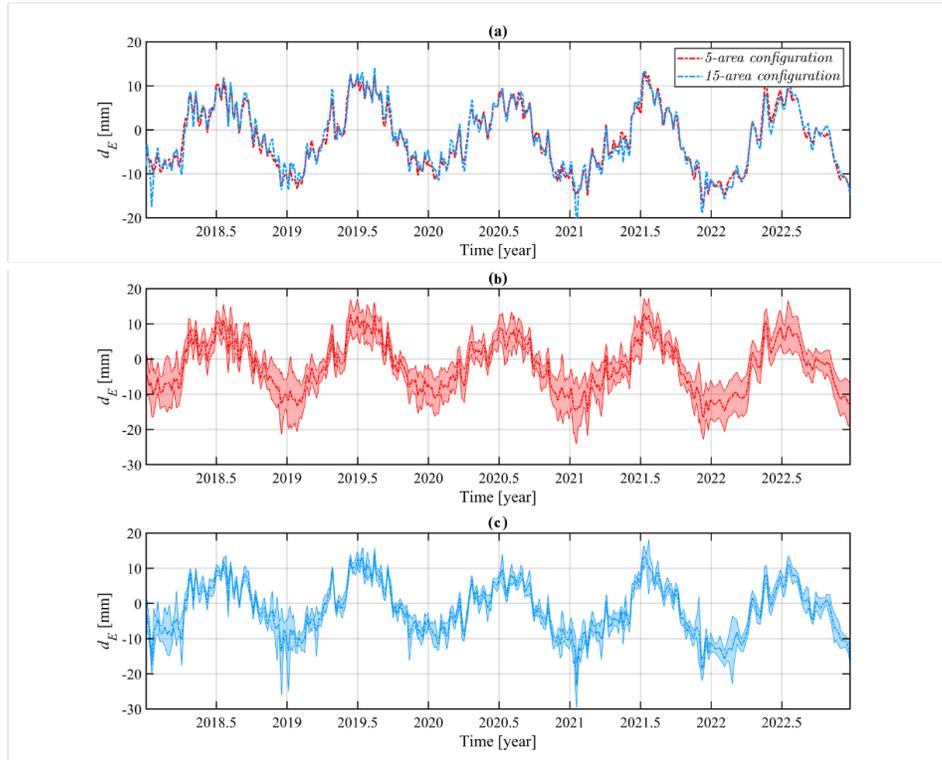


Figure 4. Schottwien Viaduct. (a) Comparison of the displacement time series in the longitudinal direction E for the 5- and 15-area grid. Confidence interval of the displacement for (b) 5-areas mesh; (c) 15-areas mesh.

## COLLAPSE ANALYSIS

Grid-based resampling of InSAR data can also be useful to identify average displacement trends preceding a bridge collapse. Post-collapse assessments to determine the root causes of a bridge failure are often complex and can benefit from

information about early patterns exhibited before a structural failure. In this context, monitoring systems can provide essential data on structural behavior, aiding forensic investigations. However, traditional structural health monitoring systems, which rely on in-situ sensors, are typically installed only on a limited number of key structures, limiting the number of cases of collapsed bridges for which monitoring data were available before the failure. In contrast, InSAR offers extensive historical datasets across wide areas, particularly well-suited for capturing progressive structural displacements over time, enabling the analysis of deformation patterns over time, thereby offering valuable early warning signals. Several cases of collapse analysis supported by InSAR data have been presented in the literature. Selvakumaran et al. [7] observed an anomalous behavior of a bridge pier affected by scour one month before its collapse; Milillo et al. [8] highlighted a continuous increase of the relative displacement between a pier and the deck of the Morandi bridge, starting 3 years before the collapse in 2018. Farneti et al. [9] interpreted the collapse of the Albiano-Magra viaduct in 2020 based on the movements of the bridge deck recorded by InSAR during 5 years before the collapse. More recently, Tavakkoliestahbanati et al. [10] published a study on Khakhovka dam, Ukraine, which collapsed in June 2023. Their analysis identified anomalous displacement patterns on the southern section of the dam in the months prior, providing insights into structural variations observed before the event.

In reference [11], a study on the collapse of a masonry bridge was carried out integrating InSAR measurements with the results of a numerical simulation of the collapse. This case study is an exemplary case highlighting that InSAR data can provide historical information that onsite investigations cannot capture, enabling discarding non-consistent collapse mechanisms during the post-collapse analysis.

The bridge was an arch masonry bridge overpassing an affluent of the Po River, in Northern Italy. After its construction, the bridge experienced several maintenance and reinforcement interventions until its collapse during a river overflow. Figure 5 shows a view of the collapse scene, taken by a drone a few days after the collapse that involved pier 2 (P2) and the two arch spans supported by pier P2.



Figure 5: The masonry bridge ruins.

Initial post-collapse assessments carried out through visual inspections pointed to a heightened vulnerability of the pier foundation, likely resulting from the degradation of protective elements. Even though geomorphological surveys revealed the presence of a dormant landslide near the bridge's southern abutment, no direct field evidence

confirmed its recent reactivation. Building on this preliminary context, early speculation was advanced that scour of pier 2 might have triggered the collapse. A later analysis was carried out using InSAR data. Figure 6 shows the displacements retrieved from the ascending orbit, of the MPs on the bridge deck (on the right of the figure) and on the road at the edge of the dormant landslide (on the left of the figure). Similar trends are found in the descending orbit. These trends confirm an uplift movement of the bridge and a downward movement of the road, consistent with the hypothesis of a reactivation of the dormant landslide. Data relevant to the bridge deck MPs have been clustered according to the profile of the bridge spans (see Figure 7). The displacement time history of the MPs is reported in the figure and enables tracing the bridge's displacement history for some years before the failure. As highlighted in Figure 7, a significant uplift affects the two collapsed bridge spans close to the landslide zone (red dots in Figure 7). The comparison of this trend with the finite element simulations of the potential collapse mechanism caused by the settlement of the collapsed pier due to scour, enables discarding such mechanisms that cannot involve an uplift of the bridge deck. On the contrary, this mechanism is consistent with the horizontal displacement of the southern abutment, most likely driven by a renewed movement of the complex landslide, which involved both rotational and translational components.

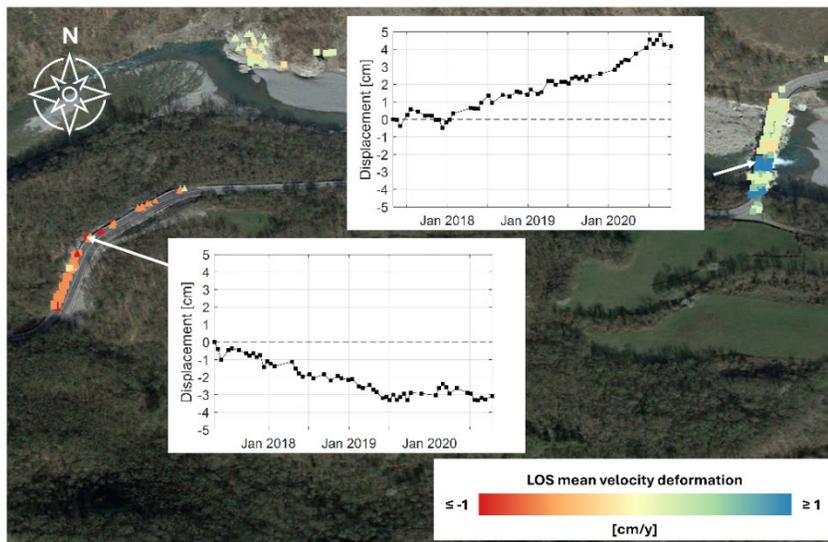


Figure 6: LOS mean velocities and deformation time series on the dormant landslide (left) and on the bridge (right).

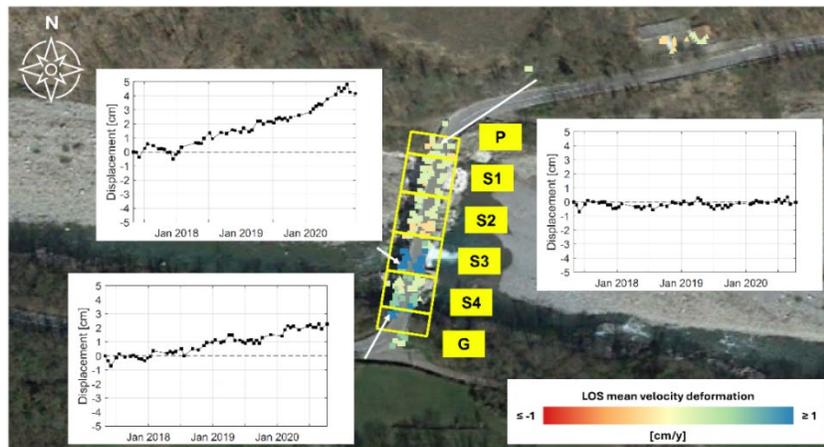


Figure 7: LOS mean velocities and deformation time series on the bridge span.

## CONCLUSIONS

This paper outlines both the potential and limitations of InSAR for analyzing structural behavior. While effective for remotely monitoring displacements, its accuracy is limited by uncertainties related to sensor properties, environmental conditions, and geometry. Key issues include spatial and temporal decorrelation, especially when merging ascending and descending data to estimate 3D displacements, which requires resampling and introduces approximation errors. Grid-based approaches can reduce uncertainty and help interpret pre-collapse trends.

Combining InSAR with numerical models and field data enhances understanding of structural failure. A case study of a masonry bridge showed how InSAR revealed uplift in collapsed spans, contradicting the hypothesis of pier settlement due to scour and instead suggesting landslide reactivation. Future improvements in automation, resolution, and data accessibility will strengthen InSAR's role in forensic and preventive monitoring. Its capacity to provide early warnings and reconstruct structural behavior over time makes it a powerful complement to traditional methods, especially for under-instrumented infrastructure.

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