

Decoupling Regional Subsidence from Structural Displacements in InSAR Time Series: The Maradona Stadium Case Study

Riccardo Liuzzo¹, *[0009-0006-5030-2543], Alessio Bonzani¹, Pier Francesco Giordano¹[0000-0003-0396-0253], and Maria Pina Limongelli¹[0000-0002-9353-5439]

¹ Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy
riccardo.liuzzo@polimi.it

Abstract. Satellite Interferometric Synthetic Aperture Radar (InSAR) has become a key tool for the large-scale monitoring of civil structures, as it enables long-term displacement measurements with millimetre-level accuracy and wide spatial coverage. However, the interpretation of InSAR measurements at the scale of individual structures remains challenging in complex urban environments, particularly when ground deformation processes dominate the observed signal. This condition is observed in several areas of the Naples metropolitan region, Italy, where widespread subsidence affects the urban environment and displacement time series derived from Persistent Scatterers (PSs) primarily reflect ground movements rather than structural response. Therefore, dedicated methods are required to isolate the component of the measured displacement that is related to structural behaviour. This work investigates the Diego Armando Maradona Stadium in the Fuorigrotta district of Naples, within an urban area affected by significant ground deformation. InSAR displacement time series derived from COSMO-SkyMed data are analysed by comparing alternative approaches for estimating and removing the subsidence contribution from PS measurements, with the objective of enhancing the visibility of displacement components representative of the stadium response. The comparison highlights how the choice of compensation strategy affects the resulting displacement signal and its interpretation at the asset level.

Keywords: InSAR, remote sensing, Structural Health Monitoring, stadium, subsidence, COSMO-SkyMed, displacement

1 Introduction

Spaceborne Interferometric Synthetic Aperture Radar (InSAR) has attracted growing interest for the monitoring of civil infrastructure. By enabling the reconstruction of displacement time series over large spatial domains and long observation periods, InSAR provides a valuable source of information for assets for which dense on-site monitoring is impractical, unavailable, or economically difficult to justify [1,2]. However, the structural interpretation of InSAR-derived measurements is not straightforward, since

displacements are measured along the satellite Line of Sight (LOS), representing only a scalar projection of the actual three-dimensional displacement field [3,4]. A further difficulty arises when the measured signal includes contributions that are not directly associated with the structural response of interest. In such cases, the observed displacement time series may represent a superposition of local structural movements and broader deformation processes affecting the surrounding area, such as regional subsidence or site-scale ground movements [5,6]. Dedicated methods are therefore required to isolate the structural component of the measured displacement, yet the issue remains only partially addressed in the literature [7–10].

In the Naples metropolitan area, ground deformation associated with the Campi Flegrei caldera affects the built environment and is clearly detectable in satellite observations [11,12]. Within this context, the roof structure of the Diego Armando Maradona Stadium was selected as a case study due to a combination of structural and geometric features. Its steel construction, large dimensions, and long-span cantilevered beams make it susceptible to thermally induced non-negligible displacement variations. Moreover, the elliptical roof geometry makes it possible to investigate how the orientation of the structural beams with respect to the satellite LOS influences the capability of InSAR measurements to reconstruct local displacement patterns at the structural scale. The present study analyses COSMO-SkyMed InSAR time series over the Maradona Stadium and its surroundings, with the aim of decoupling the local structural response from the broader deformation affecting the area. Two alternative approaches are compared for estimating and removing the regional deformation component. The resulting residual displacement time series are then used to reconstruct the displacement response of the structure and to assess whether the inferred time histories are consistent with the expected structural behaviour. The paper is organized as follows. First, the case study and the available InSAR dataset are introduced. Then, the strategies adopted to estimate and compensate for the regional deformation component are described. Finally, the residual displacement time series are analysed and discussed in relation to the expected structural response of the stadium.

2 Case study

2.1 The Diego Armando Maradona Stadium

The Diego Armando Maradona Stadium is a municipality-owned multi-purpose facility located in the Fuorigrotta district of Naples, Italy, in the active Campi Flegrei caldera. Constructed between 1952 and 1959, it currently accommodates approximately 55,000 spectators and serves as the home ground of the SSC Napoli football team. In plan, the structure has an elliptical layout, with a 105x68 m football pitch surrounded by an athletics track. The grandstand consists of three reinforced-concrete seating tiers, supported by 56 inclined ribs radially distributed along the perimeter. The roof system, added during the renovation works completed for the 1990 FIFA World Cup, comprises 28 radial steel truss beams evenly distributed along the perimeter and supporting lightweight cladding panels. Each truss has a cantilever span of approximately 42 m and is

carried by steel columns located along the outer perimeter of the grandstand at an overall height of about 33 m, as shown in Fig. 1(a). To support the interpretation of InSAR measurements, the roof was discretized into 28 azimuthal sectors, numbered clockwise, each associated with one radial truss. Each sector was further partitioned into an inner band (subscript i), facing the pitch, and an outer band (subscript o), facing the external perimeter, thus defining 56 areas in total, shown in Fig. 1(b). The orientation angle α_{beam} of each truss, defined as the clockwise rotation from the East direction to the beam longitudinal axis, as shown in Fig. 1(c) varies continuously along the perimeter over full 360° range.

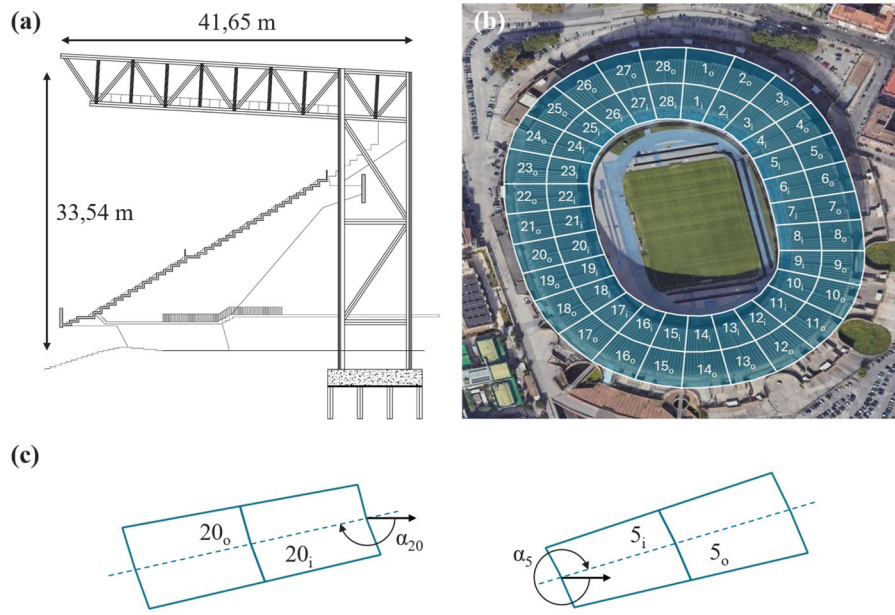


Fig. 1. The Diego Armando Maradona Stadium. (a) Grandstand cross-section; (b) discretization adopted for the analysis; (c) definition of the truss orientation angle α_{beam} .

2.2 InSAR datasets

The InSAR data used in this study were generated by CNR-IREA through the Parallel SBAS processing chain. COSMO-SkyMed images were acquired in Stripmap mode, providing a ground resolution of approximately 3×3 m, and span the period from July 2009 to March 2025. Processing was performed using the SRTM1 arcsec DEM within the WGS84 reference system. From the full track coverage, a 1 km^2 area centred on the stadium was extracted. Within this area, Persistent Scatterers (PSs) located on the stadium structure were separated from those in the surrounding urban environment. An additional elevation filter with an orthometric height threshold of 110 m was then applied to isolate roof-level PSs from ground-level measurements. The spatial distribution

of PSs for both geometries is shown in Fig. 2; mean LOS velocities are approximately -6.2 mm/yr and 9.7 mm/yr for the ascending and descending geometry, respectively. To enable the combination of ascending and descending observations at the structural scale, the roof-level PSs were assigned to the 56-area roof discretization based on their planimetric position.

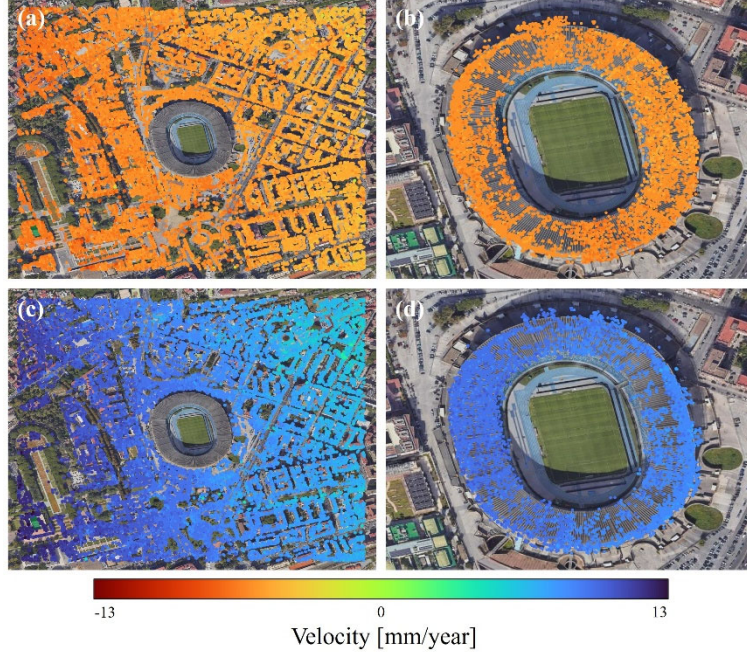


Fig. 2. Spatial distribution of PSs in the 1 km² area around the stadium for the (a-b) ascending and (c-d) descending tracks.

3 Methodology

3.1 InSAR data processing

For each radial truss, LOS displacements are expressed in a local (L , T , V) reference frame, where the L -axis is aligned with the beam longitudinal direction, the T -axis is orthogonal to it in the horizontal plane, and the V -axis is vertical. The local frame is defined independently for each area by rotating the global (E , N , U) system about the vertical axis by the angle α_{beam} , following the formulation described in [2]. PSs from the ascending and descending datasets are aggregated within each of the 56 roof areas, and a mean LOS displacement time series is computed for each geometry. Since the two datasets are acquired at different epochs, linear temporal interpolation onto a common time axis is applied prior to their combination. Assuming negligible transverse displacement ($d_T = 0$), the LOS measurements from the two geometries are inverted

to reconstruct the longitudinal and vertical displacement components, d_L and d_V , for each area. The sensitivity of the LOS geometry to longitudinal and vertical motion depends on the truss orientation: when the beam longitudinal direction is nearly aligned with the satellite LOS, the inversion becomes poorly conditioned, and the longitudinal component may be spuriously amplified. This condition affects areas 14 and 28, which are therefore excluded from the displacement analysis.

3.2 Regional subsidence modelling and removal

The regional deformation trend is estimated independently for the ascending and descending datasets using the PSs located in the area surrounding the stadium. The estimated trend is then subtracted from the LOS time series of the roof-level PSs before the displacement components are reconstructed. Two alternative approaches are considered, referred hereafter as Method 1 and Method 2. In Method 1, the regional component at each acquisition epoch is taken as the mean LOS displacement of the surrounding PSs, obtaining a background-motion time series derived directly from the observations. In Method 2, a constrained quadratic polynomial is fitted to the LOS displacement time series of the same surrounding PSs, providing a smooth parametric representation of the regional deformation trend. Goodness of fit is evaluated using the coefficient of determination R^2 . In both cases, the estimated background component is removed from the LOS measurements prior to reconstructing the structural response. Fig. 3 shows the estimated regional trends from both methods alongside the mean LOS displacement of the roof-level PSs for the ascending and descending datasets.

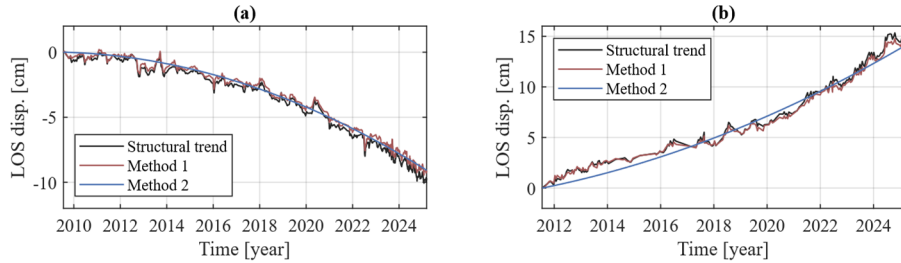


Fig. 3. Mean LOS displacement of the roof-level PSs and regional trend estimated by Method 1 (red) and Method 2 (blue) for the (a) ascending and (b) descending datasets.

4 Results

After removing the regional trend using the two approaches, the residual LOS time series were combined following the procedure described in Section 3.1 to reconstruct the longitudinal and vertical displacement components for each structural area. Fig. 4 shows the reconstructed d_L time series for the outer areas across the full roof perimeter. A clear sign reversal is observed between areas 1-13 and areas 15-27, reflecting the continuous change in beam orientation relative to the satellite LOS as α_{beam} varies along the ellipse. This behaviour is consistent with the local reference frame

convention, since the same physical motion is projected with opposite sign onto trusses located on opposite sides of the roof. Compared with Method 1, Method 2 exhibits greater short-term variability and more pronounced isolated peaks, whereas Method 1 yields smoother and more spatially coherent time histories across adjacent areas.

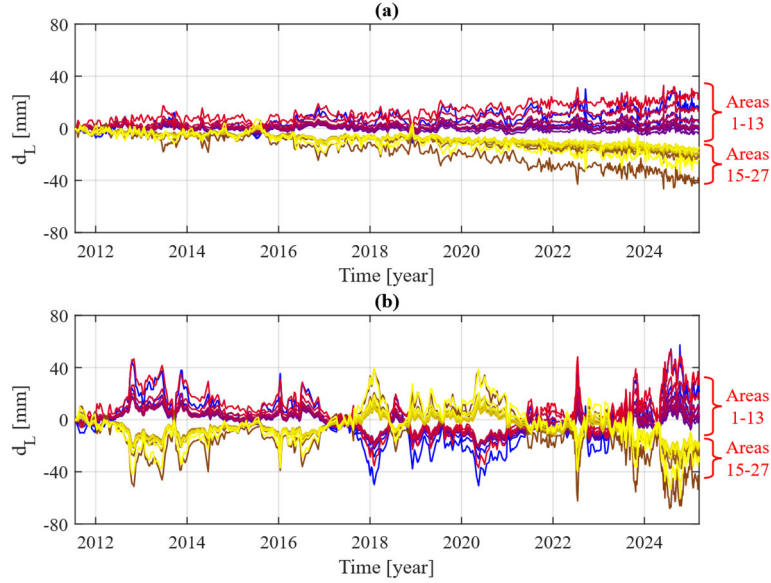


Fig. 4. Longitudinal displacement components for areas 1-13 and 15-27 computed with (a) Method 1 and (b) Method 2.

The reconstructed vertical displacement component d_V is shown in Fig. 5. Both methods reveal a marked seasonal cycle, consistent with the expected thermal expansion and contraction of the steel roof trusses. The two approaches differ, however, in the low-frequency component superimposed on the seasonal oscillation. Method 1 produces time series that oscillate more regularly around zero, whereas Method 2 introduces a residual low-frequency drift, exhibiting opposite signs in the two groups of areas. Nevertheless, a slight long-term drift remains visible in the Method 1 results as well, suggesting that the reference PS population does not yet provide a fully representative estimate of the regional trend at the stadium location. This is likely attributable to the spatial extent of the area currently used for background estimation: by including PSs over too wide region, the derived trend may reflect deformation processes that are not strictly local to the stadium area. Refining the spatial selection of the reference PSs is therefore expected to improve the separation between structural and background displacement.

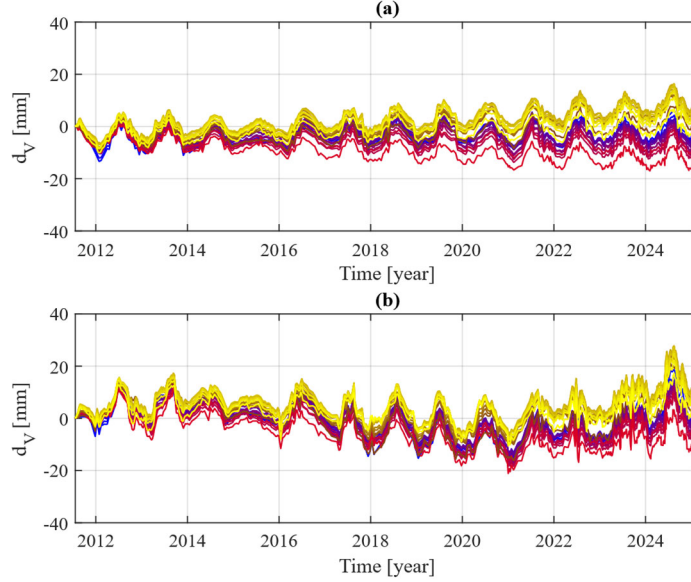


Fig. 5. Vertical displacement components for areas 1-13 and 15-27 computed with (a) Method 1 and (b) Method 2.

5 Conclusions

This study investigated the effect of background motion compensation on the interpretation of InSAR-derived displacements at the Diego Armando Maradona Stadium in Naples. The results demonstrate that the regional ground deformation affecting the area dominates the measured signal and must be accounted for before any structural interpretation can be made at structural scale. Of the two approaches considered, Method 1, based on the epoch-wise mean LOS displacement of the surrounding PS population, provided more consistent reconstructed time series and reduced drift. Despite the improved performance of this approach, a residual long-term drift persists in the reconstructed time series, indicating that the current reference PS population incorporates deformation signals not fully representative of the ground motion at the stadium location. Future work will therefore focus on spatially refining the selection of reference PSs, restricting the population to those most representative of the local background motion, with the aim of achieving a cleaner separation between regional deformation and structural response.

Acknowledgments. This study was carried out as part of the program of activities outlined with the DPC-ReLUIIS 2024-2026 project – WP6 “Monitoring and satellite data”.

References

- [1] S. Selvakumaran, C. Rossi, E. Barton, C.R. Middleton, Interferometric Synthetic Aperture Radar (InSAR) in the Context of Bridge Monitoring, in: 2021: pp. 183–209. https://doi.org/10.1007/978-3-030-59109-0_8.
- [2] P.F. Giordano, M. Kwapisz, A. Miano, R. Liuzzo, A. Vorwagner, M.P. Limongelli, A. Prota, M. Ralbovsky, Monitoring of a multi-span prestressed concrete bridge using satellite interferometric data and comparison with on-site sensor results, *Structural Concrete* (2025). <https://doi.org/10.1002/suco.202400881>.
- [3] T. Fuhrmann, M.C. Garthwaite, Resolving Three-Dimensional Surface Motion with InSAR: Constraints from Multi-Geometry Data Fusion, *Remote Sens. (Basel)*. 11 (2019) 241. <https://doi.org/10.3390/rs11030241>.
- [4] R. Liuzzo, P.F. Giordano, M.P. Limongelli, Quantifying uncertainty in InSAR-derived displacement measurements for bridge monitoring, in: *SPIE-Intl Soc Optical Eng*, 2025: p. 13. <https://doi.org/10.1117/12.3050715>.
- [5] S. Bianchini, F. Pratesi, T. Nolesini, N. Casagli, Building Deformation Assessment by Means of Persistent Scatterer Interferometry Analysis on a Landslide-Affected Area: The Volterra (Italy) Case Study, *Remote Sens. (Basel)*. 7 (2015) 4678–4701. <https://doi.org/10.3390/rs70404678>.
- [6] S. Rigamonti, G. Dattola, P. Frattini, G.B. Crosta, A Multivariate Time Series Analysis of Ground Deformation Using Persistent Scatterer Interferometry, *Remote Sens. (Basel)*. 15 (2023) 3082. <https://doi.org/10.3390/rs15123082>.
- [7] M. Zhu, X. Wan, B. Fei, Z. Qiao, C. Ge, F. Minati, F. Vecchioli, J. Li, M. Costantini, Detection of Building and Infrastructure Instabilities by Automatic Spatiotemporal Analysis of Satellite SAR Interferometry Measurements, *Remote Sens. (Basel)*. 10 (2018) 1816. <https://doi.org/10.3390/rs10111816>.
- [8] G. Martin, A. Hooper, T.J. Wright, S. Selvakumaran, Blind Source Separation for MT-InSAR Analysis With Structural Health Monitoring Applications, *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* 15 (2022) 7605–7618. <https://doi.org/10.1109/JSTARS.2022.3190027>.
- [9] P.F. Giordano, G. Miraglia, E. Lenticchia, R. Ceravolo, M.P. Limongelli, Satellite interferometric data for seismic damage assessment, *Procedia Structural Integrity* 44 (2023) 1570–1577. <https://doi.org/10.1016/j.prostr.2023.01.201>.
- [10] S. Quqa, A. Palermo, F. Ubertini, A. Marzani, Regional-scale bridge condition monitoring using InSAR displacements and environmental data, *Struct. Health Monit.* (2024). <https://doi.org/10.1177/14759217241302369>.
- [11] S. V. Samsonov, P.J. González, K.F. Tiampo, A.G. Camacho, J. Fernández, Spatiotemporal Analysis of Ground Deformation at Campi Flegrei and Mt Vesuvius, Italy, Observed by Envisat and Radarsat-2 InSAR During 2003–2013, in: 2014: pp. 377–382. https://doi.org/10.1007/978-3-642-32408-6_84.
- [12] F. Bellucci, J. Woo, C.R.J. Kilburn, G. Rolandi, Ground deformation at Campi Flegrei, Italy: implications for hazard assessment, *Geological Society, London, Special Publications* 269 (2006) 141–157. <https://doi.org/10.1144/GSL.SP.2006.269.01.09>.