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Analysis of multi-source satellite-derived displacement data for structural monitoring of masonry heritage buildings

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Abstract.

Historical masonry structures, such as churches and towers, represent a fundamental part of our cultural heritage but are particularly vulnerable due to both aging and the external influences they are subjected to. In this context, Structural Health Monitoring (SHM) plays a crucial role in assessing structural integrity and preventing damage. In recent years, satellite remote sensing data, such as those obtained through interferometric techniques (InSAR), have gained increasing relevance in SHM applications, also due to the free availability of pre-processed datasets from missions like Sentinel-1 (European Ground Motion Service - EGMS). However, the direct use of such data may often be limited, as they are provided in a pre-processed form, reducing the user ability to customize and adapt the analysis. This study presents a comparison between pre-processed EGMS data and data obtained through user-controlled processing using dedicated software, with the aim of evaluating the advantages and limitations of each approach. Using data obtained through user-controlled processing allows for the targeted selection of reliable points while discarding those considered inconsistent or of low quality, thus ensuring a more robust and tailored analysis. This processed data could be useful to calibrate a numerical model, enabling the joint optimization of mechanical parameters and external imposed actions (e.g., displacements), thus improving the prediction of structural behaviour and supporting more robust SHM models.

Keywords: Type your keywords here, separated by semicolons ;

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1. Introduction

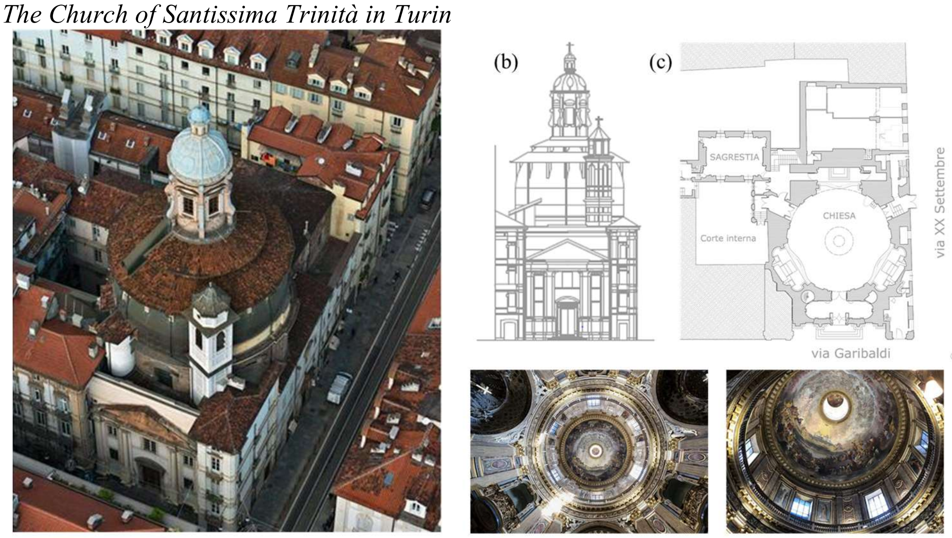
The past decade has witnessed events that have increasingly revealed the vulnerability and fragility of infrastructures, buildings, and historical architectural assets. Particularly in urban contexts, entire districts have proven to be highly exposed to natural hazards exacerbated by climate change, including floods and landslides, as well as to extreme events such as earthquakes (Tarantini, R., et al., 2022, 2023). Although the extraordinary magnitude of these events is undoubtedly a factor, it is equally clear that insufficient or inadequate structural monitoring and maintenance have frequently contributed to worsening their consequences. Within this framework, there is a growing recognition of the necessity to systematically observe and monitor structures. In Italy, for example, new technical codes for the monitoring and maintenance of bridges and viaducts have been introduced in recent years (MIT & CLSP, 2020). This highlights the need for effective technologies capable of continuously assessing and managing the structural health state. Consequently, there is an increasing interest in identifying new methodologies for the integration and integration of heterogeneous data sources for Structural Health Monitoring (SHM) (Farrar & Worden, 2012), with the aim of acquiring the widest possible range of structural information. In this regard , in situ traditional monitoring represents one of the data sources, enabling the assessment of the structural behaviour through different kind of information. Complementary to this, the use of satellite remote sensing data is emerging as a valuable resource for SHM. In particular, Interferometric Synthetic Aperture Radar (InSAR) techniques (Rodriguez & Martin, 1992) provide the ability to measure displacements with millimetric precision. Initial uses of satellite interferometric data in the SHM domain have been reported for the detection of anomalies in single structures (Sohn et al., 2002), linear infrastructures (Lazecky et al., 2015), and even entire urban areas (Arangio et al., 2014; Bonano et al., 2013; Cigna et al., 2014). Alongside InSAR data, which are capable of providing displacement information, other types of satellite data have recently been employed within the framework of structural monitoring, namely geophysical data, which can offer insights into the surrounding context of the structure (Coccimiglio, 2025; Coccimiglio et al., 2022).

2. Satellite data for monitoring displacements

In this research of new and effective technologies and methodologies aimed at facilitating the collection of information on structural health conditions, satellite remote sensing plays a significant role. Specifically, satellite technologies that enable the acquisition of displacement information. In the field of SHM, the detection and continuous monitoring of displacements represent a pivotal resource for supporting the observation and preservation of both natural and built environments. Such capability is of particular relevance for the analysis of complex phenomena, including subsidence, ground settlement, and differential movements, ensuring an uninterrupted, non-invasive, and cost-effective means of assessing the structural conditions of structures and infrastructures. In this context, InSAR technology proves particularly valuable due to its ability to provide displacement information through radar measurements that are independent of weather conditions and sunlight availability. By utilizing two distinct satellite orbits, displacement can be projected along two separate directions. The methodology relies on multi-interferogram techniques, analysing time series of full-resolution differential interferograms from SAR acquisitions. This approach minimizes noise from various sources and enables the extraction of both temporal displacement trends and average velocities for each individual Measurement Point (MP) (Kotzerke et al., 2022). For further details on this technology, the reader is referred to (ReLUIS, 2023). The use of such data enables a detailed analysis of deformation phenomena affecting both structures and foundation soils, offering valuable support for the monitoring of structural conditions. Over the past three decades, the inherent flexibility and high precision of InSAR, along with its derived techniques, such as Differential InSAR (DInSAR) (Giordano et al., 2022), have driven the continuous advancement of technologies for displacement monitoring in both natural and built environment. Different classes of satellite platforms support the acquisition of InSAR data for ground displacement monitoring. The Copernicus Sentinel-1 constellation, under the European Space Agency's Copernicus program, provides C-band SAR data with high spatial and temporal coverage, forming the basis of the EGMS dataset (EC & ESA, 2024). The Italian CosmoSkyMed constellation, operated by Agenzia Spaziale Italiana (ASI) , employs X-band SAR sensors to deliver high-resolution ground motion observations with flexible revisit times. Similarly, the German TerraSAR-X mission utilizes X-band SAR to achieve sub-meter spatial resolution, enhancing the capacity to monitor subtle deformations. The Japanese ALOS-2 satellite, operated by JAXA, incorporates L-band SAR (PALSAR-2), which offers deeper penetration and robust performance in vegetated areas for displacement mapping. Finally, Canada's RadarSAT-2 system operates in the C-band, supporting frequent revisit cycles and reliable displacement measurement capabilities. Together, these missions offer

complementary spatial resolutions, revisit intervals, and wavelength characteristics, facilitating robust InSAR-based structural and geotechnical monitoring.
Focusing on the Italian territory, data from the two European satellite constellations, Sentinel-1 and CosmoSkyMed, are widely used. For Sentinel-1 constellation, displacements data can be collected through the EGMS platform, where the data are already processed by the ESA, or through other platforms such as the Alaska Satellite Facility (ASF), where it is possible to gather information from raw images and then process them using specific software. In the first case, however, the data have already been processed and the parameters used during processing are unknown; consequently, data control and verification become more difficult, although the time required to download and obtain the final product is significantly reduced. To gain greater control over data processing and the selection of processing parameters, it is more useful and advantageous to work starting from raw data. However, as previously mentioned, this approach requires greater effort in terms of time, computational resources, and storage capacity. In this paper, a comparison between two different types of datasets is presented. The first dataset is that obtained from the EGMS platform, while the second dataset is obtained from the processing using the SARPROZ software (version 7 marzo 2025) (Perissin, 2025). This allows for the assessment of potential differences, advantages, and disadvantages of both approaches. The case study is a monumental masonry building located in Turin, the Church of Santissima Trinità.

Case study: The Church of Santissima Trinità in Turin



(a) (d) (e)

Figure 1. The Church of Santissima Trinità: (a) External view, (b) Section, (c) Plan, (d) and (e) Internal view of the dome

The Church of Santissima Trinità in Turin was commissioned in 1598 by the confraternity of the same name and designed by the ducal architect Ascanio Vitozzi. Its central plan features a circle inscribed with a double equilateral triangle, forming a six-pointed star that emphasizes the symbolism of the Trinity. The structure is notable for its unusual architectural composition, where the dome and lantern dramatically dominate the lower cylindrical walls. The interior, mainly decorated in polychrome marble, was extensively redecorated in the 18th century by Filippo Juvarra and his pupil Giovanni Pietro Baroni. The church sustained significant damage during the bombing of Turin in 1943, particularly to the choir, which was reconstructed post-World War II. Restoration works on the dome began in 2018, supported by the Compagnia di San Paolo, as part of a broader initiative to preserve Turin historic religious buildings.

3. Methodology

In this research work, the authors focus on the use of InSAR data acquired by ESA's Sentinel-1 satellite constellation, obtained through two different approaches. On one hand, pre-processed data available through the EGMS platform are employed. In this case, the data are provided at various processing levels, depending on user requirements. Once the Area of Interest (AoI) is selected via the EGMS portal, historical time series of measurement points can be directly downloaded and used. Time series are available from 2018 to 2023. On the other hand, data derived directly from raw images are used. In this case, data are provided in Single Look Complex (SLC) format on the ASF portal (https://asf.alaska.edu/). After download, the data were processed by the authors, allowing for greater control over the entire processing workflow and the selection of processing parameters. In the following sections, the characteristics of both datasets will be described.

3.1 EGMS InSAR data

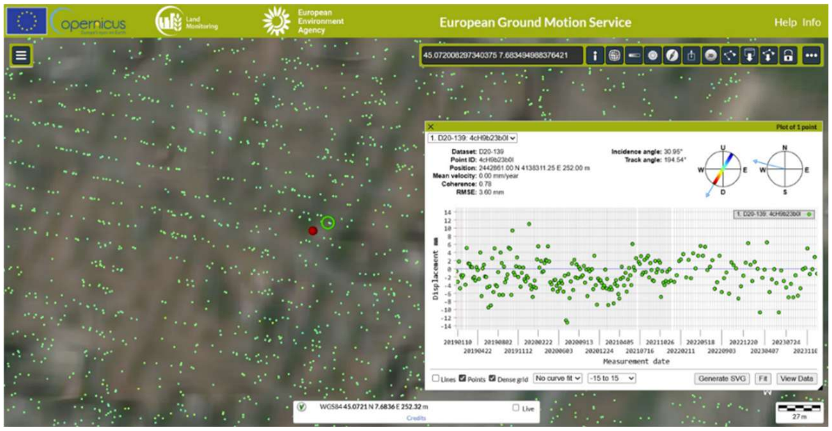


Figure 2. View of EGMS platform with Measurement Points (MPs) and time series

The EGMS is the latest component of the Copernicus Land Monitoring Service (CLMS), with data available from 2018 to 2023. It measures physical ground displacements at specific points detected via satellite, processed through various levels of analysis. The EGMS data is freely accessible to anyone interested in ground motion, and it is also characterized by high measurement precision. On the official EGMS website, InSAR data is provided in three distinct product types: *Basic,* it offers InSAR displacement data in the satellite Line-of-Sight (LoS) direction, accompanied by geo-localization and quality metrics for each measurement point. *Calibrated, c*onsidered the main EGMS product, it addresses to the needs of most users. It builds upon the Basic product but includes an additional level of processing, displacement values of InSAR measurement points are referenced to a model derived from Global Navigation Satellite System (GNSS) time-series data, thus making the measurements absolute. Finally, *Ortho*, it uses the discrete viewing angles available from the Calibrated product to generate two additional layers: one representing purely vertical displacements, and the other showing purely east-west displacements. For further details, see (Capes & Passera, 2023; Ferretti et al., 2023; Kotzerke et al., 2022). Figure 3 shows a schematic overview of the possible applications of the different EGMS product levels, based on their level of processing. In the context of this study, which concerns an architectural heritage structure, all three product levels could be utilized. However, the authors focus primarily on the Calibrated product, as it offers higher accuracy and spatial resolution.

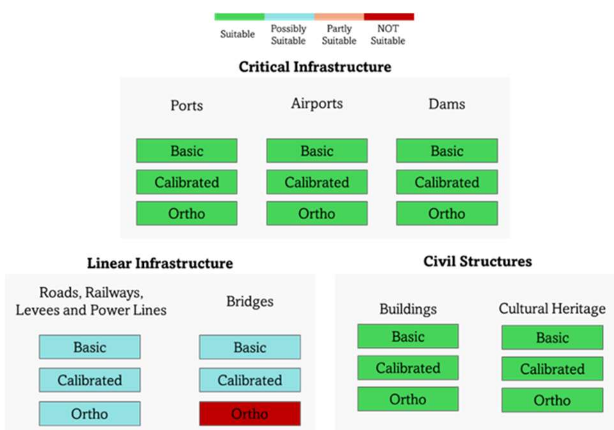


Figure 3. Application of EGMS products in civil engineering and infrastructure field

Once the AoI has been selected on the EGMS platform, it is possible to download the time series data based on geometry (ascending or descending) and subswath configuration. In the case of EGMS, they are acquired in Interferometric Wide (IW) Swath mode, specifically employing a type of ScanSAR mode known as "Terrain Observation with Progressive Scan" (TOPS) (Ferretti et al., 2023).

3.2 InSAR data processed using SARPROZ

In the second step of the analysis, the attention was focused on raw images of Sentinel-1. The first step involved the collection of Single Look Complex (SLC) data from the ASF Data Search Vertex portal (https://search.asf.alaska.edu). The dataset covers the AoI between 2019 and 2023 and consists of scenes acquired in IW mode, with descending orbit geometry and vertical-vertical (VV) polarization. The SLC format preserves both amplitude and phase information, essential for interferometric and multi-temporal InSAR analyses. The dataset was processed using SARPROZ, a software environment dedicated to SAR and InSAR applications (https://eo59.com/products-sarproz). Orbit files were set, and a master image dated 2020-07-22 was selected based on spatial and temporal baseline criteria. The AoI was defined to include the monitored structure and its surroundings. A total of 169 images were processed. Co-registration was performed using cross-correlation for scenes with restituted orbits and orbit-based alignment for scenes with precise orbit information. Scenes without precise orbits were processed using cross-correlation techniques. Interferometric connections between the images were established using a star graph configuration centred on the master image, ensuring a dense temporal network (Figure 4).

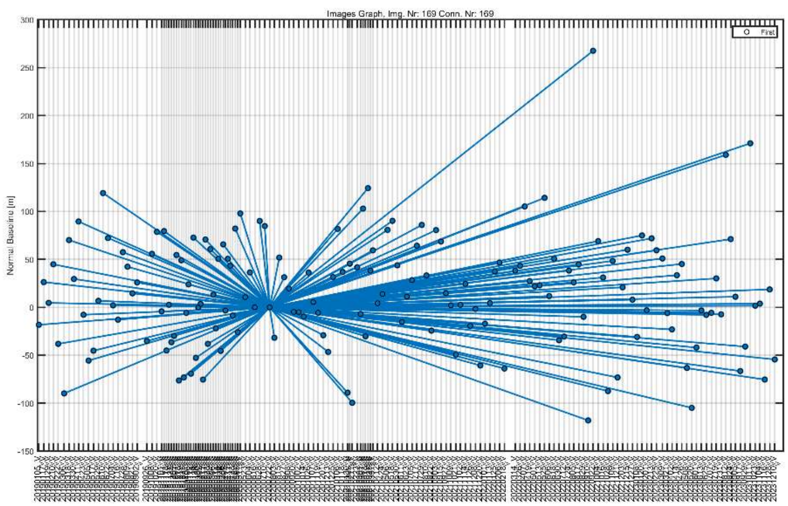
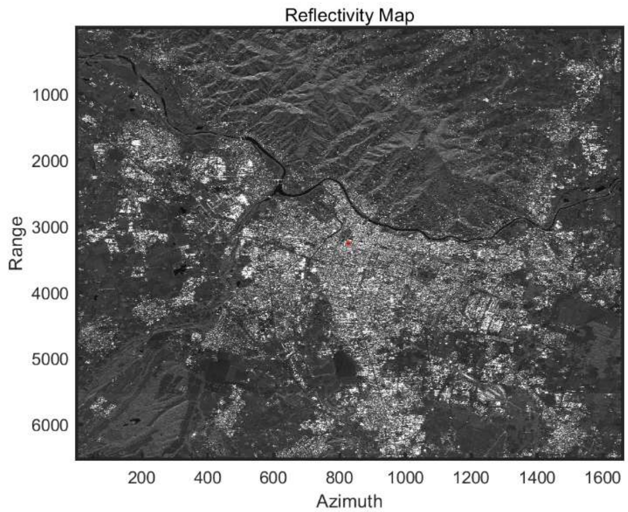
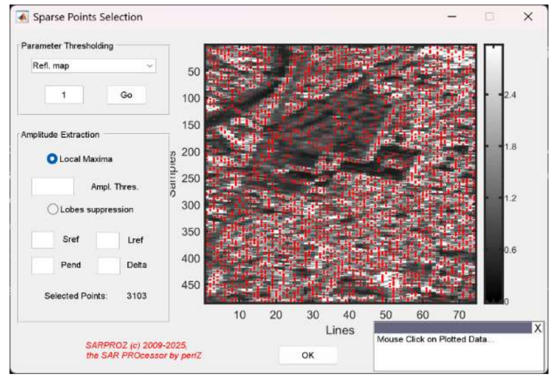


Figure 4. Star graph representation of interferometric connections, showing the temporal and normal baselines of all images with respect to the selected master (2020-07-22)

The site processing phase aimed to identify coherent scatterers within the scene. A reflectivity map was generated along with the Amplitude Stability Index (ASI), which quantifies the temporal consistency of radar backscatter. A selection mask based on local maxima was applied to isolate sparse but reliable points. An external high-resolution Digital Elevation Model (DEM) from the Copernicus dataset was integrated to improve geolocation accuracy. Ground Control Points (GCPs) were manually selected, and the DEM, along with a synthetic amplitude image, was projected into SAR coordinates (azimuth and range) to ensure geometric consistency (Figure 5a). A detailed interferometric analysis was conducted on a Small Area (SA) surrounding the target structure using SARPROZ Small Area Processing module. The area was selected directly from the reflectivity map, and a threshold of 1 (on a scale from 1 to 3) was applied to retain only high-quality scatterers. The sparse points selected through this filtering process are shown in Figure 5b. A reference point with a high ASI value was selected to serve as a stable phase anchor. The interferometric phase components were then decomposed in order to estimate key parameters, including the linear displacement trend, which captures long-term ground or structural movement; the height residuals, which refine the elevation data relative to the external digital elevation model (DEM); and the seasonal trends, which account for periodic variations typically associated with thermal expansion.



(a)



(b)

Figure 5. (a) Reflectivity map of the area of interest with manually selected Ground Control Points (GCPs) overlaid. The GCPs support accurate geocoding and coordinate referencing during the InSAR processing chain, and (b) Selected sparse points in the small area surrounding the target structure, obtained by applying a reflectivity threshold and local maxima filter to identify reliable coherent scatterers.

4. Results and discussion

After data collection and processing, in the case of SARPROZ, the results were visualized on Google Earth in order to analyse their spatial distribution over the buildings (Figure 6). Subsequently, four closely spaced points were selected on the structure of interest (Figure 7). From the comparison between the two datasets, focusing on the building of interest and the surrounding area, it would seem that EGMS provides a greater number of points compared to those obtained with SARPROZ. While this may initially seem to be an advantage of the EGMS data, the higher point density is actually a consequence of the filtering procedures applied. In the case of EGMS, analyses are conducted separately for each subswath, and points are selected based on amplitude values with a temporal coherence threshold of approximately 0.5. Conversely, SARPROZ performs a combined analysis across all subswaths. As a result, points that appear in one subswath but not in another are excluded from the analysis, as they are considered unstable. Moreover, SARPROZ adopts a stricter temporal coherence threshold of 0.6. Therefore, it would appear that although fewer in number, the points derived from the SARPROZ analysis exhibit higher quality and greater stability. In Figure 8, time series of the selected points are shown. From the comparison of the time series, it can be observed that the points exhibit very similar values, with generally limited oscillations ranging between +3 mm and -3 mm, although some points show slightly larger variations. In the case of point P24 from the EGMS dataset, an increase in oscillation amplitude is noticeable toward the end of the time series. Since the structure does not appear to be affected by any movement or damage, it could be hypothesized that these variations are due to the limited stability of the point itself, as it has a temporal coherence of only 0.66, in contrast to the other three points, which exceed 0.80. Other information on the selected points can be found in Table 1.

Table 1. Comparison between selected points of Sarproz and EGMS: ID, latitude, longitude, height, velocity, coherence, standard deviation (Std) of displacements and mean of displacements

	ID	Lat	Lon	h [m]	vel [mm/year]	Coherence	$Disp_{Std}$ [mm]	$Disp_{mean}$ [mm]
SARPROZ	1803	45.07209	7.683617	248.3	-0.2	0.92	2.25	0.5483
	1765	45.07195	7.683671	264.1	-0.5	0.86	1.39	-0.2515
EGMS	20	45.07197	7.683567	258.9	0.5	0.86	2.75	1.2824
	24	45.07196	7.683607	252.9	-0.1	0.66	4.05	0.4660

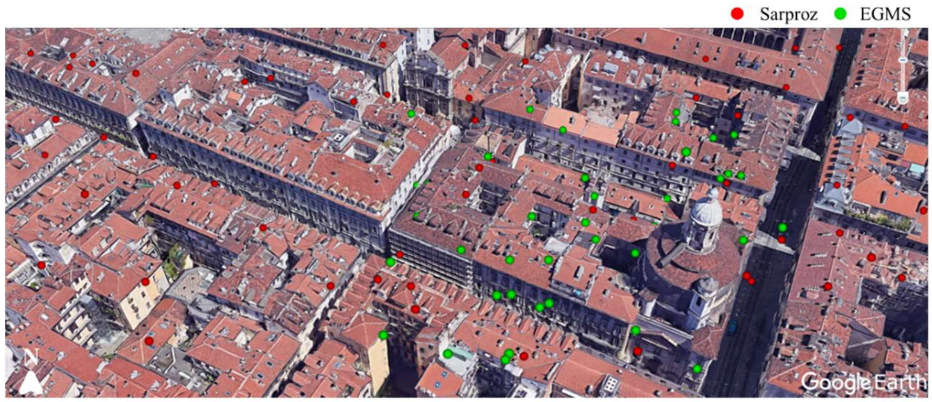


Figure 6. Points of EGMS (green) and SARPROZ (red) on Google Earth

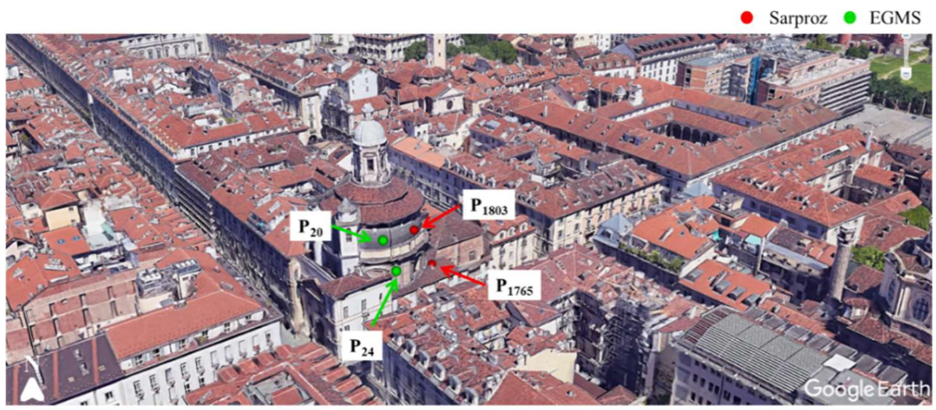


Figure 7. Selected points of EGMS(green) and SARPROZ (red)

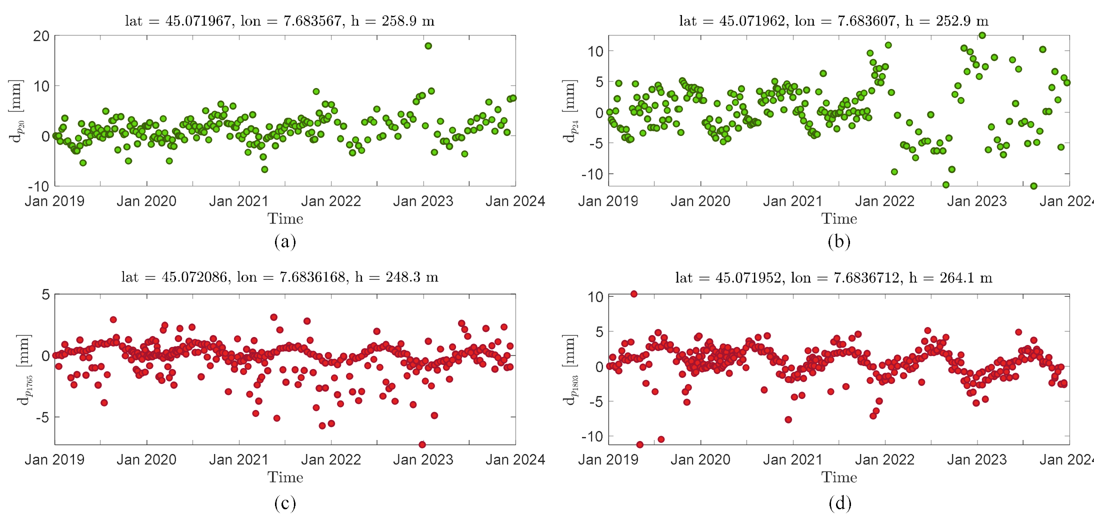


Figure 8. Time series of selected points: (a)P_{20}, (b) P_{24}, (c) P_{1803}, and (d) P_{1765}

5. Conclusions

This study explores the application of InSAR satellite data for SHM of historical masonry buildings, focusing on the case of the Church of Santissima Trinità in Turin. A preliminary comparative evaluation was conducted between pre-processed data from the EGMS and data obtained through user-controlled processing using the SARPROZ software.

The analysis highlights both the potential and the limitations of each approach. While EGMS offers immediate access to dense datasets with minimal processing effort, user-controlled workflows allow for greater customization, improving the reliability and interpretability of the results. In particular, the ability to refine coherence thresholds and manually select stable measurement points proves essential when monitoring complex structures such as historical buildings. Despite requiring more resources, the SARPROZ-based approach would demonstrate superior data quality and spatial precision. These findings underscore the importance of choosing the most suitable processing strategy based on monitoring objectives, structure characteristics, and data quality requirements. In conclusion, the choice of dataset is closely dependent on the objectives of the analysis and the desired level of detail. Certainly, for preliminary studies, data provided by the EGMS represent a highly useful and readily accessible resource. However, for more detailed and advanced analyses, managing the data processing and interpretation directly is preferable to achieve more accurate and tailored results.

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