HEMOC: a Project for Monitoring of Cultural Heritage in the City of Como, Italy

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Abstract

In the second half of 1900 the city of Como has been intensely affected by land subsidence, especially in the “Convalle” historical area near the lake. Its effects may cause concerns to the conservation and safety of cultural heritage (CH) buildings located in the city centre. Supported by funding from the NextGenEU program, the HEMOC ("HEritage MOnitoring in Como") project has main objective to design and implement a network of seven new permanent GNSS stations. These stations are based on low-cost GNSS technology, which allows continuous 3D observation for monitoring CH sites in town. GNSS-based observations are integrated with in-situ monitoring data and will be used to calibrate ground-deformation maps obtained from Advanced DInSAR processing of high-resolution CosmoSkyMed data. The results of the monitoring sensors are implemented in a digital platform for data storage and visualization.

Keywords: Cultural Heritage, GNSS, InSAR, Monitoring

1 Introduction

The city of Como (Italy) has played an important historical role since the Ancient History, mainly due to its strategic position at one of the Southern branches of the Como Lake, which represents an access point for crossing the Alps and connecting Italy and Switzerland. This resulted in the development of several human settlements during past centuries, which left a valuable Cultural Heritage (CH) spanning from some Roman remains through the Middle-Age buidings and fortifications up to some important pieces of contemporary architecture.

During the second half of 1900, the city of has been intensely affected by land subsidence, caused by the interaction of multiple natural and anthropogenic factors (Colombo et al., 1998; Eskandari and Scaioni, 2023). This phenomenon has been slowing down in recent decades, remaining significant in the “Convalle” area near the lake, where the most pieces of CH are located. Its effects may cause concerns to the conservation and safety of historical buildings located in the city centre, requiring the integration of in-situ and urban-scale monitoring of ground deformation. While a few important buildings have been monitored by engineering geodesy techniques, the impact of land subsidence on the general vertical settlement of the town was observed by means of the repeated measurement of an altimetric network based on optical levelling. As summarized in Scaioni et al. (2025), the period of these monitoring campaigns (#8 in total) was from 1975 to 2004, when a pre-existing altimetric network was expanded with the specific aim of investigating land-subsidence behaviour and its effects on the built heritage. During this period, a slowing down of the process could be observed, probably due to the positive effects of some countermeasures that had been undertaken, mainly the reduction of water extraction through artificial wells from deep aquifer layers. Considering the last levelling network measurements (1997-2004), the vertical displacements stabilized at the natural average value of -2 mm/year, with a higher velocity near the lake (-11.3 mm/year).

On the other hand, the periodical measurements of the levelling network were able to provide vertical displacements in correspondence of its benchmarks, with no information on the remaining part of the territory and buildings. In recent decades, the growing diffusion of microwave remote-sensing satellites has been providing data for millimetre-level ground deformation monitoring over wide-areas. Moreover, the measurement of the levelling network was time consuming and could be repeated only after few-year intervals, leading to a definitive stop in 2004. The development of Advance Differential Interferometric SAR (Synthetic Aperture Radar) techniques such as Persistent Scatterer Interferometry (PSI – Crosetto et al., 2015) could provide data covering the entire urban areas, where the presence of good reflecting surfaces may result in a high coherence in the multitemporal SAR images. In Eskandari and Scaioni (2023) some analyses on the town of Como are reported based on two types of SAR data: (i) medium-resolution ERS1/2 data collected from April 1992 - April 2004; and (ii) high-resolution Cosmo-SkyMed data collected from April 2010 - May 2012. The former presented a temporal overlap with the last levelling observations and could be compared based on geospatial interpolation methods to deal with the diverse spatial distribution. These results demonstrated a good correlation between both types of altimetric deformations, considering the spatial resolution of the adopted SAR data. The latter data could not be compared with levelling observations due to the lack of temporal overlap. On the other hand, these were compared to some results from the local monitoring network of the Como Cathedral, showing high correlation (see Fig. 1). On the other hand, the application of PSI technique can be retained reliable only in the presence of other benchmarking observations, at least in some parts of the city.

Supported by the NextGenEU program as part of the NODES Extended Partnership ("Digital and Sustainable North West") – Spoke 3 ("Tourism and Culture Industry") – see NODES, 2025 –, the HEMOC ("HEritage MOnitoring in Como") project has as its main objective to design and implement a network of seven new permanent GNSS stations before its end scheduled on spring 2025 (Sect. 2). These stations are based on low-cost GNSS technology developed by the GReD S.r.l. company (from now on "GReD" – Subsect. 2.3), which allows continuous 3D observation for monitoring six cultural heritage sites in town (Subsect. 2.2). One additional GNSS station is located on the tower of the Baradello Castle on the top of a hill overlooking the town, to be used as local reference (see Fig. 2). GNSS-based observations are integrated with in-situ monitoring data and used to calibrate ground-deformation maps obtained from Advanced DInSAR processing of high-resolution CosmoSkyMed data.

The results of the monitoring sensors are implemented in a digital platform for data storage and visualization (Sect. 3). This platform is being developed by the partner company DkR S.r.l. (from now on "DkR").

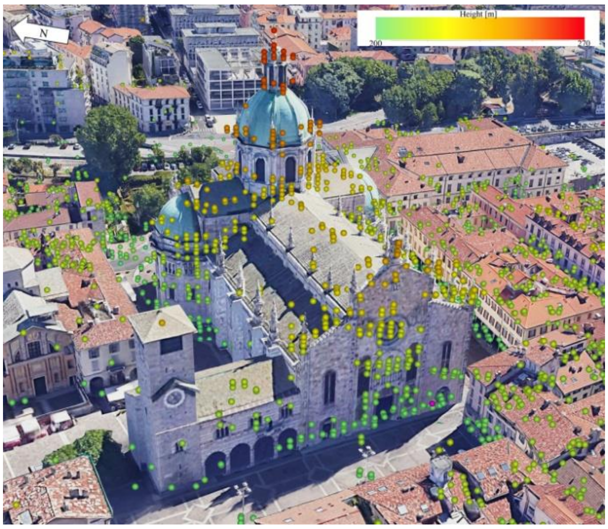

Figure 1. Persistent Scatterers processed through Multi-Temporal InSAR over the area of Como Cathedral (points are colored with the estimated height).

2 The HeMOC GNSS network

The development of the GNSS HeMOC network of continuosly operating stations was design with multiple purposes, as discussed in the following subsection.

2.1 Purpose of the HeMOC network

First of all, the new GNSS stations should provide precise 3D observations on different areas of the city, useful to evaluate different trends of land subsidence. As displayed in Figure 2, stations of the HeMOC network were located in different areas where land subsidence has been recently observed on the basis of a preliminary analysis from PSI techniques based on Sentinel-1 data in the period 2018-2023. To extend the investigated area, the HeMOC network also integrates data from the continuosly operating reference station (CORS) of the public SPIN3 network and the European EPN network (station with code COMO in Fig. 2). GNSS data are computed in differential mode w.r.t. the reference station HEM1 located on the top of Baradello Castle, which is a medieval castle on the top of a hill outside the area affected by land subsidence. In this configuration, the longest baseline in the network is 3.2 km long, but any station could be alternatively used as reference. It is also feasible to differentiate GNSS observations w.r.t. an external CORS. This option would allow the analysis of possibile long-term ground deformation trend regarding the entire area where the town is settled.

Tridimensional displacements observed by the HeMOC network can be used to correct local biases in the ground deformation pattern detected from the analyses of different SAR data (high-resolution CosmoSkyMed and medium-resolution Sentinel-1 data).

2.2 Locations of GNSS stations

New GNSS stations are located in correspondence of important CH buildings in town, some of them under monitoring based on in-situ measurement (e.g., the Cathedral and the Basilica of San Giacomo). At the moment of writing, five stations have been installed and they are operating together with the “COMO” CORS (see their location and photos in Fig. 1):

1. Baradello Castle (HEM1);
2. Cathedral of Como (HEM3);
3. Basilica of San Giacomo (HEM4);
4. Gallio College (HEM5); and
5. Palazzina Nord in Villa Olmo (HEM7).

Other two GNSS station will be installed during spring 2025 on the roof of Archaeological Museum Paolo Giovio (HEM2) and on the terrace located on the top of the War Memorial (HEM6).

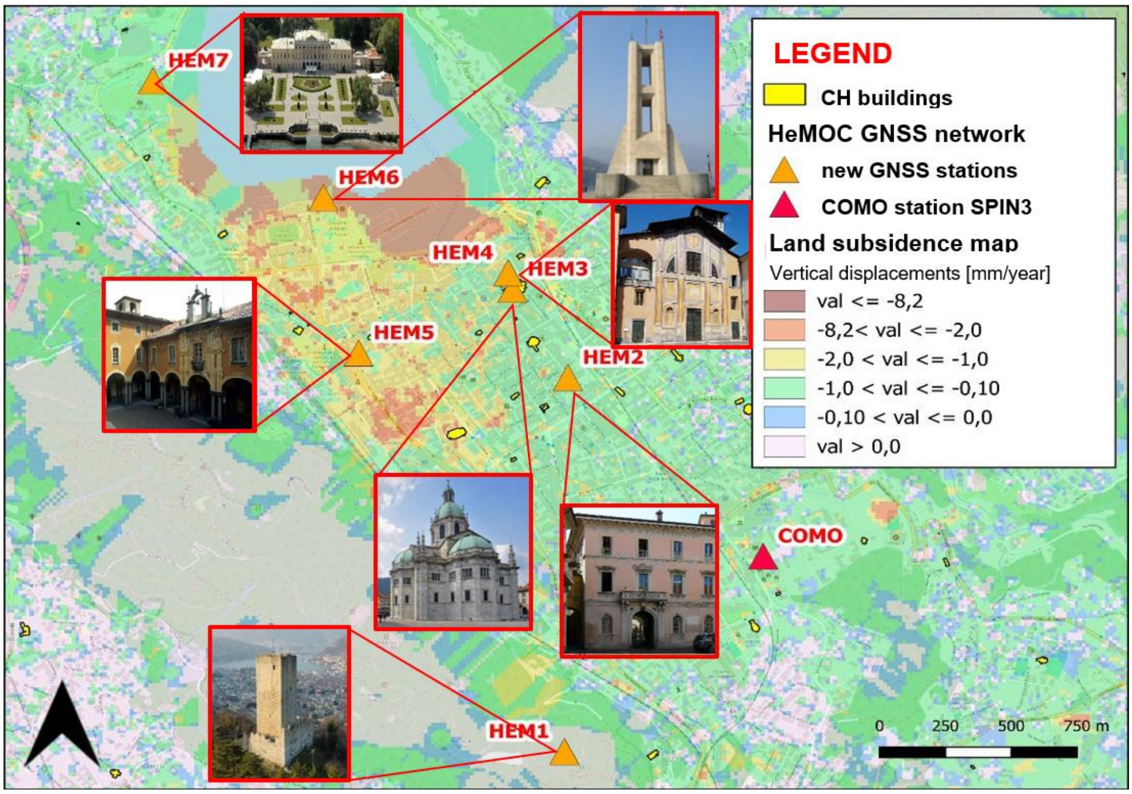

Figure 2. Map of Como town showing the locations of the GNSS stations of the HeMOC network together with vertical deformation rates created through the application of Persistent Scatterer Interferometry (PSI). Codes of the selected Cultural Heritage (CH) buildings shown in sub-windows refer to Subsection 2.2.

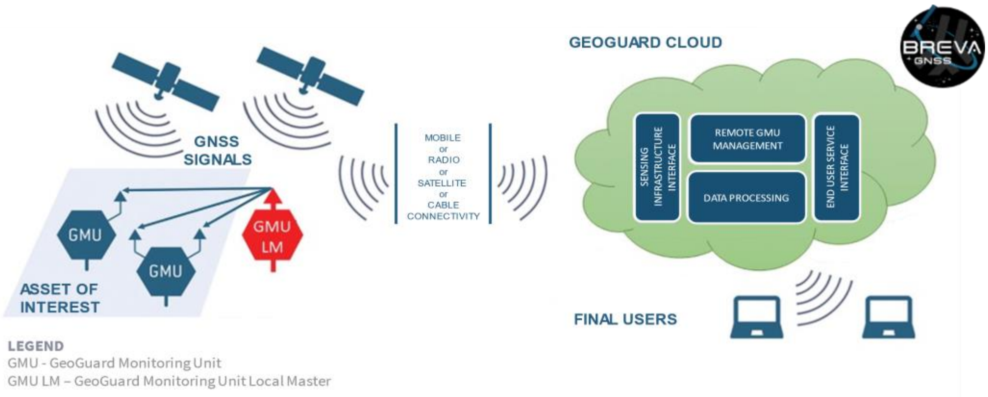

Figure 3. Scheme of the GeoGuard® GNSS monitoring service developed by GreD.

2.3 GNSS technology

The GNSS technology implemented in the HeMOC network is based on two main components, which have been developed by GReD (see Fig. 3) and consitute the the GeoGuard® GNSS monitoring service (Tagliaferro et al., 2018; Caldera et al., 2022). These include: (i) the GeoGuard® Monitoring Unit; and (ii) the cloud-based system BREVA®.

2.3.1 The GeoGuard® Monitoring Unit

The GeoGuard® Monitoring Unit (GMU) is able to control one or two consumer-grade single- or dual-frequency GNSS receivers and antennas, to be installed on the building/structure to be monitored. The GMU can also host other types of sensors and is equipped with a bidirectional communication system as interface with the cloud-based system BREVA®.

GMUs are innovative GNSS IoT sensors, which are based on mass-market GNSS receivers and antennas. On each site to be monitored, one GMU serve as local reference station (GMU LR). In the case of the HeMOC network, the GMU LR is located on Baradello Castle (HEM1) and is equipped with a single antenna/dual-frequency receiver.

In addition to the GMUs, geodetic class receivers from the networks of permanent stations present in the area are also integrated into the GNSS monitoring network, as the case of COMO station in the HeMOC network.

2.3.2 The cloud-based system BREVA®

The cloud system BREVA®, developed by GReD, is designed for processing GNSS data for geodetic and environmental monitoring. BREVA® can collect and organize the GNSS data from connected GMUs, verify the integrity of the data flow, carry out processings and re-processings automatically, as well as analyze the results and make them available to the end users (see workflow in Fig. 3). BREVA® is based on the open-source code goGPS (Realini and Reguzzoni, 2013; Herrera et al., 2016). It applies a baseline-processing approach, based on the undifferentiated and uncombined joint least-squares adjustment method.

In HeMOC the software is set to process L1 code pseudoranges and carrier phases transmitted by the GPS and Galileo satellite constellations, using orbits and satellite clocks provided by the Center for Orbit Determination in Europe (CODE). BREVA® does not allow for the direct estimation of ionospheric and tropospheric effects, but uses a priori models, combining CODE and Vienna Mapping Function (VMF) data. Finally, BREVA® calibrates the variations of the L1 phase center, compensating for interference and anisotropy related to the antenna, and offers the possibility of obtaining hourly and daily batch solutions, allowing for a flexible management of the monitoring results (see next subsection).

2.4 Some initial results

Five permanent GNSS stations of the planned HeMOC network have been installed and are in operation at the beginning of February 2025. The remaining stations (HEM2 and HEM6) should be established by March 2025.

The first GMU was set up at the Gallio College (HEM5, single frequency) and has been operational since 22nd May 2024. Considering that the initial two weeks of operation for a new GMU are necessary for internal setup, we have reported here two examples of data acquisition considering stations HEM4 and HEM5. In both cases, hourly and daily batch solutions are reported. While in the future the station HEM1 at Baradello Castle will serve as reference station, so far this station is still considered in setup. The BREVA® cloud system allows each combination of reference-monitored point to be selected for processing relevant baselines, thus other combinations have been chosen for each example in order to test different lenghts (1.7 km in Example 1 *vs* 0.6 km in Example 2). GMU installations considered in these examples are shown in Figure 4.

Figure 4. Installations of new GMUs in stations HEM4 (on the left) and HEM5 (on the right).

2.4.1 Example 1: station HEM5 w.r.t. COMO

Figure 5 shows an example of daily/hourly 3D displacements of HEM5 point at Gallio College calculated w.r.t. COMO station (at a distance of approx. 1.7 km). The observed period is from 28th May 2024 to 20th February 2025. As expected, daily results are less noisy than hourly ones. Larger noise can be observed during summer months, motivated by the higher moisture in the air and the long baseline. In addition, the horizontal components do not show significant displacements, while a smaller uplift can be observed.

2.4.2 Example 2: station HEM5 w.r.t. HEM4

Figure 6 shows an example of the daily 3D displacements of HEM5 point at Gallio College, but this time calculated w.r.t. to HEM4 point at Basilica di San Giacomo (approx. 0.6 km far away). The observed period is from 28th October 2024 to 19th February 2025. The shorter length of the baseline results in quite stable and not significant displacements. No clear correlation with temperature can be observed.

3 Visualization of monitoring data

The data visualization platform developed by DkR has been designed according to core principles aimed at ensuring an intuitive and efficient user interface. These include:

- interface simplicity;
- visibility of essential elements;
- immediate feedback;
- ease of information access; and
- adherence to users' mental models.

The objective is to deliver an effective experience for a broad spectrum of users, ranging from industry professionals to non-specialists, by enabling smooth and accessible interaction with complex data models. The interface design prioritizes clarity, consistency, and usability, incorporating comprehensive UX strategies to enhance accessibility and user satisfaction. A dedicated design system has been created specifically for the project, ensuring visual and functional consistency across the various components of the interface. This approach facilitates either the ongoing maintenance and the integration of new features. Each interface element has been thought to guide users through the process of exploration and analysis, promoting direct interaction with 3D models and intuitive navigation of the city map of Como (see Fig. 7).

Additionally, the platform's interface has been engineered to accommodate various input methods, from traditional mouse and keyboard interactions to virtual-reality (VR) controllers, ensuring a consistent and seamless user experience across different platforms.

3.1 Framework for data visualization

The *Babylon.js* framework was selected for managing 3D content in the data visualization platform. *Babylon.js* provides optimal control over materials, textures, and lighting, enabling high-quality and fluid visual rendering. Additionally, it supports immersive VR experiences, which are a key-component of the project, offering an interactive and engaging way to explore the CH under study. For the web interface, *React* was chosen, which ensures dynamic and responsive data management, making it easier to develop a user-friendly and highly interactive interface. *React* allows for the creation of modular and reusable components, enhancing the application's maintainability and scalability. Its integration with

Babylon.js facilitates a seamless user experience, ensuring smooth and intuitive navigation between the 3D models and the overall interface.

3.2 3D models of buildings

Three-dimensional models of the monitored buildings were meticulously created using photogrammetric surveys and high-resolution photographic data. The modeling process aimed to achieve the highest possible level-of-detail, while adhering to the constraints imposed by current web-based rendering technologies and commercially available VR viewers. This method facilitated the production of precise and detailed representations of historic structures, which are instrumental in analyzing material degradation and structural deformations. To enhance the visual presentation, a custom shader was developed in alignment with the project's design system.

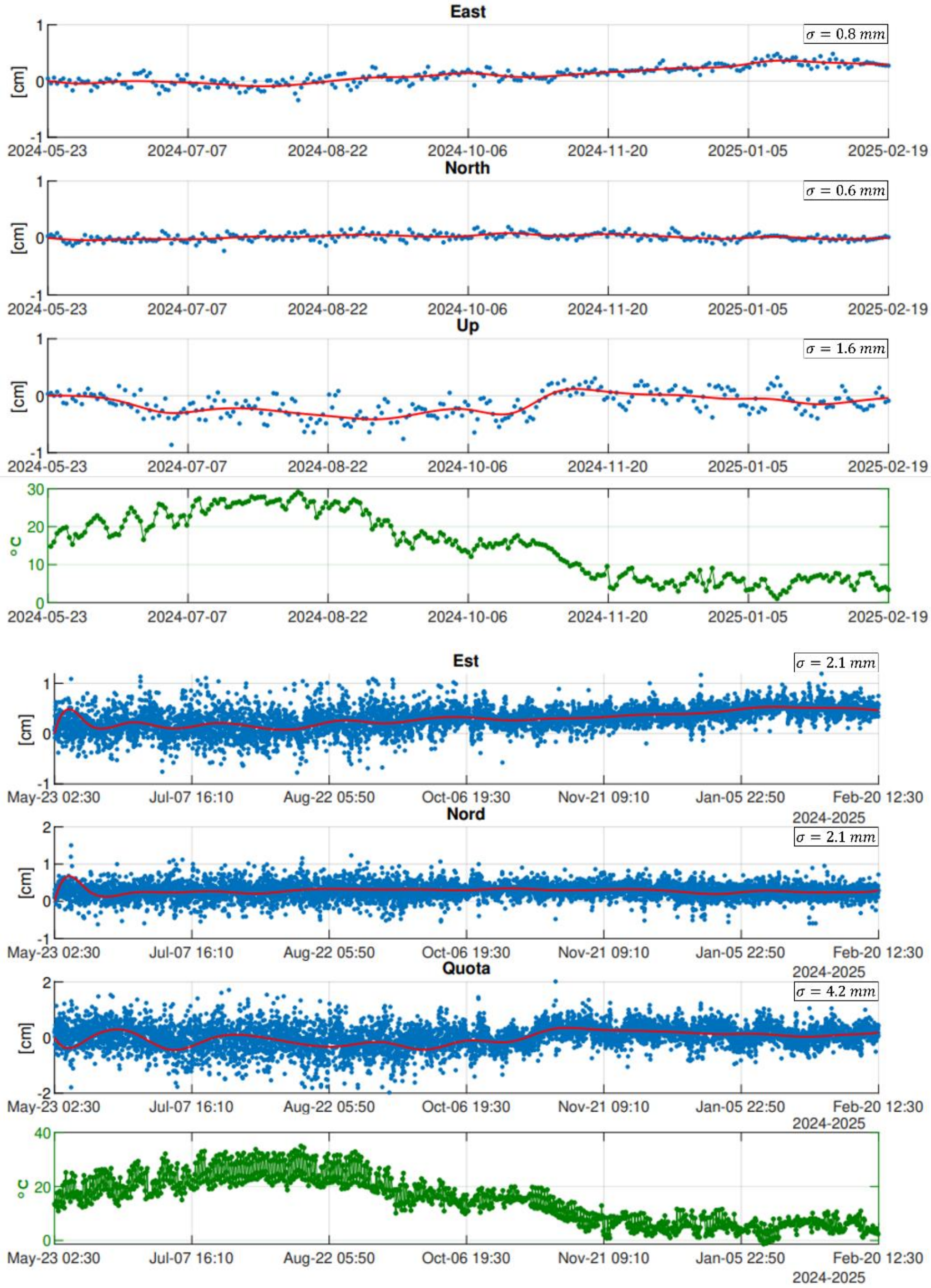

Figure 5. Daily (at the top) and hourly (at the bottom) 3D displacements of the HEM5 point (at Gallio College) w.r.t. COMO station. Points have been interpolated using splines; standard deviations refer to residuals w.r.t. interpolations. The average temperature is reported at the bottom.

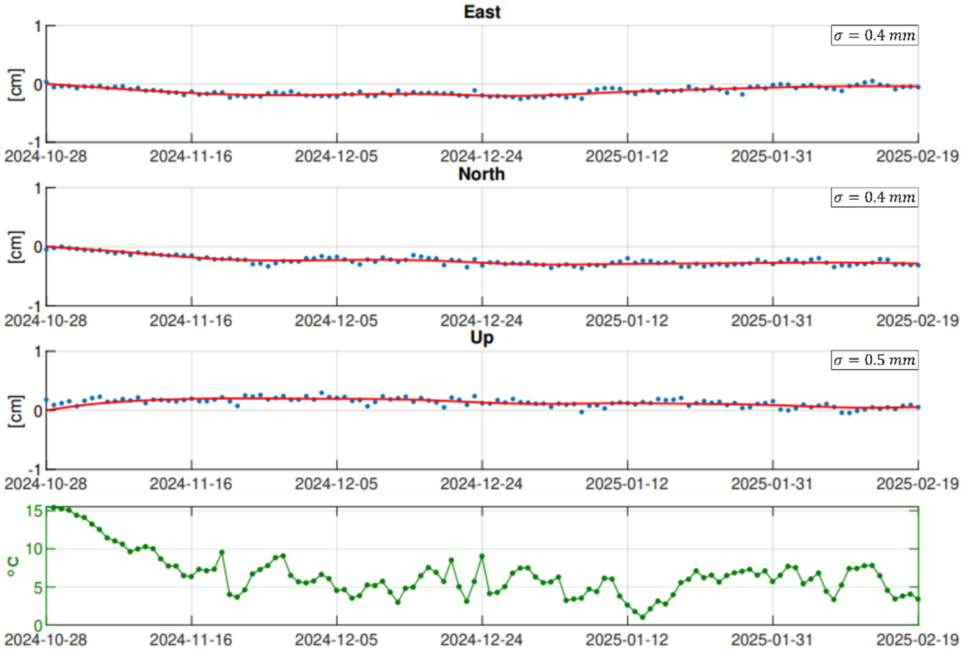

Figure 6. Daily 3D displacements of the HEM5 point (at Gallio College) w.r.t. HEM4 point (at Basilica di San Giacomo). The average temperature is reported at the bottom.

Figure 7. The map of Como town used as main menu for the data-visualization platform.

This shader renders the buildings and their surroundings in a retro-futuristic aesthetic, providing a visually distinctive and easily identifiable style. Furthermore, the models were augmented with semi-transparent volumetric elements (Fig. 8), designed to represent the historical progression of survey data. These elements enable users to more intuitively comprehend structural variations over time, thereby enhancing the analysis and interpretation of long-term changes.

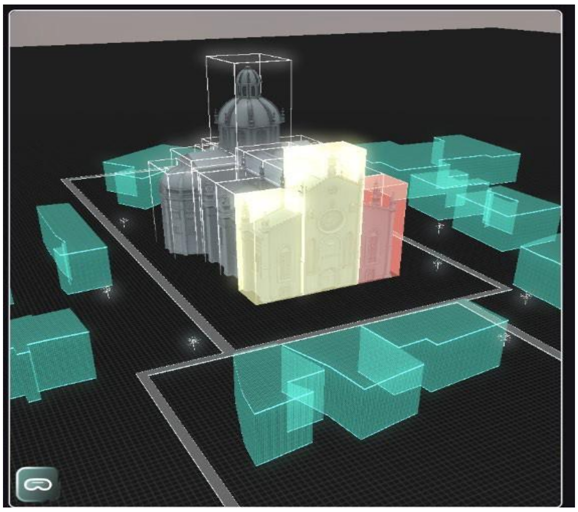

Figure 8. 3D model of the Como Cathedral from the data-visualization platform, where prisms have been selected to identify different zones for displaying displacements within time.

3.3 Web interface

The main web-interface features an interactive map of the city of Como, serving as a central hub for accessing monitoring sites (Fig. 7). Those buildings monitored in the project are highlighted using a specific color scheme, differentiating them from other structures in the city, which are depicted in a stylized manner to minimize visual complexity and aid in user orientation.

This map enables users to select individual buildings of interest and view the corresponding monitoring data, which includes 3D models (see an example in Fig. 8), historical deformation records, and satellite monitoring results derived from DInSAR data processing. This centralized and cohesive design ensures quick, intuitive, and visually consistent access to information, enhancing the platform's effectiveness in facilitating data-driven decision-making. Moreover, the 3D visualization of individual buildings features smooth navigation and interactive controls, allowing effortless exploration of various monitoring sites. These features empower users to analyze complex datasets with greater ease and comprehension, thereby improving their overall experience and understanding of the information presented.

4 Conclusions and developments

The HEMOC project ("HEritage MOnitoring in Como") has the main goal to install seven new GNSS permanent stations in some historic buildings in the city of Como. These stations are based on a low-cost GNSS technology, which allows continuous monitoring of 3D displacements. At the current time (February 2025), five GNSS stations have been installed and are fully operational, while the remaining ones will be in the coming months. At the same time, the dedicated platform for data visualization is in an advanced stage of development. This platform will allow different types of users to access the data with different profiles, encouraging intuitive and three-dimensional consultation by end users.

Once completed, the HeMOC network of GNSS permanent stations will provide useful data for the calibration and integration of satellite observations coming from the processing of medium-resolution Sentinel-1 and high-resolution COSMO-SkyMed SAR images.

Beyond the relevance of the HeMOC project for the city of Como, the proposed solution would represent a prototype potentially extendable to other historic city centres.

Acknowledgements

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