DIGITAL TWINNING FOR A SAFE COASTAL NAVIGATION: GNSS INTEGRITY REAL-TIME ANALYSIS IN WEBGIS WITH LOW-COST EQUIPMENT

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ABSTRACT

The real-time analysis of Global Navigation Satellite System (GNSS) integrity information is a precious requirement for the enhancement of safety in coastal navigation. At the same time the spread of open-source WebGIS technologies and low-cost Internet of Things (IoT) hardware equipment opened new scenarios for dynamic analyses into geospatial web visualization platforms. The focus of the paper is addressed on the generation of a low-cost WebGIS visualization platform for the real-time analysis of the GNSS integrity information during coastal navigation of ships. The framework is composed of a WebGIS platform connected with a computation module inside Anaconda Python platform, that real-time analyzes the GNSS integrity from a low cost GNSS IoT receiver. This application can be useful for improving the safety of navigation and the effectiveness of rescue operations at sea. The use of JavaScript opensource libraries and Python language and low-cost smartphone sensors allowed us to produce a low-cost digital twinning solution for the improvement of safeness in coastal navigation, available for municipalities and private companies. Future improvements may consider the integration of further modules that can optimize the quality of integrity calculation and the extension of the application offshore.

Keywords: *GNSS; integrity; WebGIS; IoT; Coastal navigation; Opensource.*

1. INTRODUCTION

Safety in maritime navigation is a sensitive issue, and accurate and reliable positioning has a key role in maintaining and increasing it. IMO (International Maritime Organization) specifies the performance requirements that a radio-navigation system must meet (IMO, 2011). The requirements are expressed in terms of accuracy, integrity, availability and continuity, and refer to different navigation phases, i.e. in ocean waters and in harbor entrance, harbor approaches, and coastal waters; of course, according to the cases, the requirements are more stringent. In this scenario, the integration of artificial intelligence and automation allowed the navigation of Maritime Autonomous Surface Ships (MASS) refining collision-avoidance navigation (Zhang et al., 2021).

Global Navigation Satellite System (GNSS) are navigation systems based on constellations of artificial satellites and are able to provide Position, Velocity and Timing (PVT) to a potentially endless number of users, worldwide and in all weather conditions (Kaplan & Hegarty, 2017). GNSS includes four systems: GPS, Glonass, Galileo and BeiDou (Jin et al., 2024). They are very similar to each other, and they are conceived to be compatible and interoperable.

GNSS are currently used in many fields, in terrestrial, air and maritime context, for technical, business or personal applications (Hassien et al., 2024). In maritime, the required performance of GNSS is detailed in (IMO, 2001), also in this case expressed in terms of accuracy, integrity, availability and continuity. Accuracy is the degree of conformance between the estimated or measured parameters of a craft at a given time and its true parameters at that time.

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Integrity is the ability to provide users with warnings within a specified time when the system should not be used for navigation. Availability is the percentage of time that an aid, or system of aids, is performing a required function under stated conditions; availability consists in signal availability, i.e. availability of a radio signal in a specified coverage area, and system availability, i.e. availability of a system to a user. Continuity is the probability that having a fault-free receiver, a user will be able to determine position with specified accuracy and to monitor the integrity of the determined position over the (short) time interval applicable for a particular operation within a limited part of the coverage area.

The most critical requirement for GNSS concerns the integrity; indeed, GNSSs are not able to deliver information about the integrity of the provided data. This shortcoming is particularly felt in safety-of-life applications such as aviation, and precisely in this context there was the development of augmentation systems which can fill the GNSS gaps. To provide integrity in the aviation context, three augmentation systems have been developed: Aircraft-Based Augmentation System (ABAS), Satellite-Based Augmentation System (SBAS) and Ground-Based Augmentation System (GBAS).

SBAS and GBAS need complex space and/or terrestrial infrastructures, such as GNSS reference stations at ground and additional artificial satellites; on the other hand, ABAS only uses information available onboard. Although the augmentation systems have been developed to meet the stringent integrity requirements of civil aviation, they have been successfully adapted to work in other contexts such as maritime or urban applications.

Two ABAS implementations are possible: Receiver Autonomous Integrity Monitoring (RAIM) and Aircraft Autonomous Integrity Monitoring (AAIM).

RAIM is based only on GNSS measurements, while in AAIM, GNSS measurements are merged with other onboard available sources, such as compass, inertial sensors, altimeters or clocks.

RAIM can provide a valuable contribution to safety in maritime navigation; indeed, RAIM is able to detect the presence of anomalous measurements, often referred to as blunders or outliers, alerting the user about the reliability of the PVT solution provided by the GNSS (Sturza, 1988; Brown, 1996; Brown & Chin, 1997). RAIM can detect anomalous solutions and also identify outliers, in order to reject them, allowing improvements in accuracy and a continuous positioning service. RAIM techniques consist of checking the self-consistency of redundant measurements; an inconsistency among the measurements indicates the presence on anomalous measurements. The use of multiple GNSS systems increases noticeably redundancy, in turn improving the RAIM ability of identifying anomalous measurements. RAIM techniques are finally able to provide Protection Levels (PLs), which define a region of the space containing the true position of the receiver with a fixed probability. PLs are compared with suitable threshold values, called Alarm Limits (ALs), defined in accordance with the considered application; in case PL exceeds AL, the GNSS solution is considered not reliable by RAIM.

RAIM was developed for aviation, but subsequently its performance has been largely analyzed outside the aviation context; for instance, in (Kuusniemi et al., 2004; Kuusniemi et al., 2007; Castaldo et al., 2014; Angrisano et al., 2013) RAIM is profitably applied to signal-degraded scenarios. Also in maritime domain, RAIM has been applied, demonstrating good results (Mink, 2016; Zalewski, 2019; Porretta et al., 2016, Gaglione et al., 2017). In maritime navigation, ad hoc RAIM algorithms should be used considering the context concerned. In particular, it should be considered that maritime navigation is mainly carried out in a good visibility scenario with a good amount of available GNSS satellites; this allows a satisfying redundancy, favorable for RAIM applications. The anomalous measurements, in this context, are mainly related to multipath from sea or, more rarely, to anomalies in the satellite clock or ephemeris; it is possible setting consequently the RAIM parameters, such as the probability of false alarm and of missed detection, or the a priori uncertainties of the measurements.

In maritime navigation, GNSS supported by RAIM can provide great benefits to the safety aspects, mainly because RAIM provides the PL, which define the boundaries of a volume surrounding the ship, where the ship itself is, with known probability; this information can be used by the authorities for the traffic management or by the ship commander for improving the separation among the ships, increasing safety and optimizing the traffic.

Considering the possibility of sharing geospatial information, the diffusion of Geographic Information Systems (GIS) and their web applications (WebGIS) allowed specialists to store, visualize and manage combinations of raster and vectorial geometric dataset and semantic information (Van Oosterom et al., 2002). In this way, the spread of geospatial information on the web through the development of WebGIS, diffusing this kind of application in numerous fields of research, has enabled the management of geospatial data in various fields of application including the management of urban transportation infrastructures (Santoso et al., 2019), the analysis of air pollution (Yakubailik et al., 2018), monitoring of forest damage (Piragnolo et al., 2021), improvement of energy efficiency in urban areas (Amado et al., 2018), valorization of touristic cultural heritage itineraries (Scianna et al., 2021), acoustic mapping of the vehicular traffic (Dardanelli et al., 2017), etc.

Considering this scenario, the parallel spread of low-cost sensor applications in electronics, based on IoT technologies, offered a fundamental contribution to WebGIS applications, introducing the possibility of making real-time spatial data analysis, processing the IoT acquisitions into WebGIS structures (Congiu et al., 2023; D'Ippolito et al., 2026). The IoT integration inside WebGIS structures opened new possibilities related to territorial analysis in many fields of research: localization of power plants related to renewable energy solutions (La Guardia & D'Ippolito, 2024), spatial and temporal WebGIS visualization of water quality (Balla et al., 2022), visualization of seismic risk in infrastructures (Mazzei & Quaroni, 2022), real-time dispatching and control of power grids (He et al., 2021). The possibility of obtaining real-time data acquisition from the real environment using low-cost IoT solutions offered specialists the opportunity to expand the research on Digital Twin (DT) applications, where the geospatial representation integrates the real-time behavior of the visualized system (Tomko & Winter, 2018). The idea of DT started in the field of robotics and automation engineering some decades ago and considers the development of a replica of a real model, that allows to control the behavior of its counterpart in real-time (Singh et al., 2021). This concept was recently applied to territorial analysis fields, creating the Urban Digital Twins (UDT), where the real-time analysis is processed in GIS (Weil et al., 2023). Furthermore, though the Geospatial Science presence in DT is not explicit, a considerable percentage of DT case studies contain elements of Geospatial discipline (Metcalfe et al., 2024).

The evolution of UDT applications generated the new concept of City Information Models (CIM) (Xue et al., 2021) extending the spread of to digital twin cities (Deng et al., 2021; Martella et al., 2023). The spread of CIM applications allowed experts to improve the quality of urban planning operations, but, at the same time, led new challenges regarding the quality of data to adopt, the not simple interoperability between different sources of dataset and the limited computing resources (Bigorra et al., 2022). In this scenario the development of digital twinning applications developed with opensource technology seems to be a valid strategy for a wide diffusion of these applications for municipalities and private companies (La Guardia et al., 2024).

In maritime navigation, considering the domain of surface ships, the DT concept was introduced in the early 2000s expressing great potential but initial slow trend of progress due to the lack of hardware and software solutions, remote sensing technologies, satellite communication facilities and other components not sufficiently developed at that time (Innac et al., 2021; Madusanka et al., 2023). Recent technological advancements allowed experts to focus their interest on the development of ship digital twinning applications finalized to autonomous navigation (Kinaci, 2023), to improve the safety on board (Briguglio & Crupi, 2024), or to help ship operations in seaways predicting hydrodynamic performances for the maneuvers (Lee et al., 2022). The possibility to generate realistic simulation in a virtual environment offered by DT applications allowed to improve the safety and sustainability of maritime operations using Autonomous Surface Vessels (ASVs) experimentations, identifying different ranges of complexity in digital twinning functionalities (Menges, & Rasheed, 2024).

In this scenario, our experimentation is based on a low-cost digital twinning application for coastal ship navigation finalized to the dynamic online WebGIS visualization of the horizontal PL surrounding the ship, based on the real-time GNSS integrity analysis. The experimentation was performed along the coast of Messina (Italy), using a low-cost GNSS equipment, inside a smartphone device, to acquire GNSS signals and integrating a Python module to perform real-time integrity calculations and a WebGIS visualization system based on the open-source Leaflet libraries (JavaScript). This solution was conceived as a DT module that can be implemented in all coastal navigation frameworks aimed at improving the quality of navigation avoiding expensive solutions. Preliminary approaches to this research were recently presented in (La Guardia et al., 2025).

The paper is organized as follows: Section 2 illustrates the framework of the DT application, Section 3 describes the functionalities of the WebGIS platform, Section 4 analyzes strengths and weaknesses of the adopted solution, and, finally, Section 5 makes an overall analysis of the work with some indications of possible future improvements.

2. MATERIALS AND METHODS

The developed platform is based on the integration of different modules (**Fig.1**), real-time connected to providing the WebGIS visualization of the protection level during navigation.

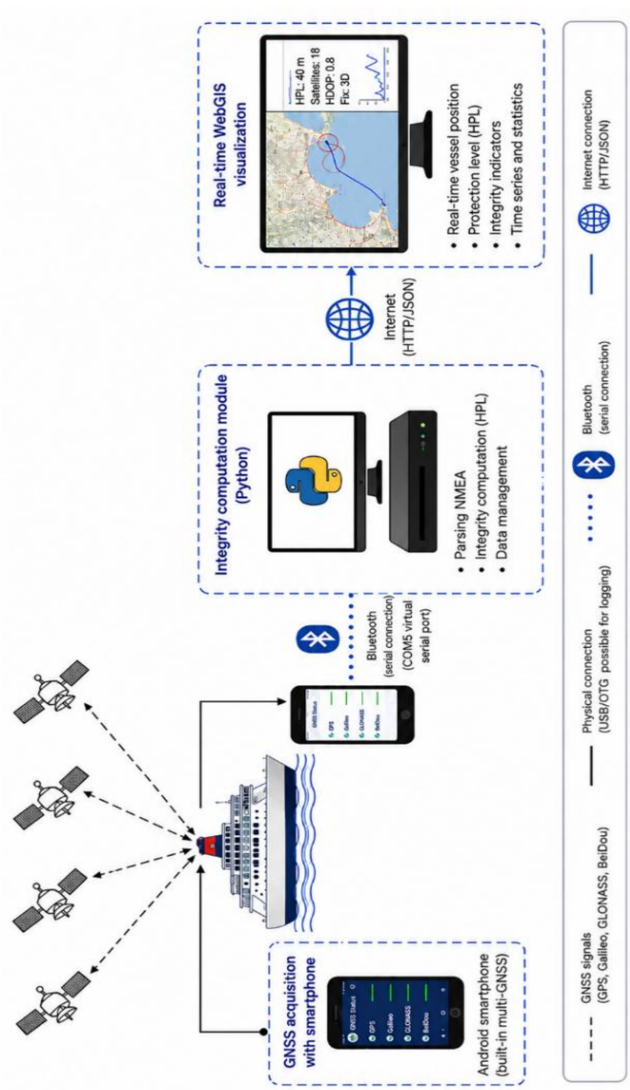

Fig. 1. The general framework.

The core of the structure is represented by the GNSS integrity computation module, that allows us to calculate the horizontal PL on the basis of the real-time data acquired from the low cost GNSS equipment that caught the signal provided by satellites. The GNSS integrity computation module was incapsulated in a Python module and connected on one side to the IoT GNSS equipment, and on the other side to a WebGIS + database structure to provide the real-time web visualization of the computation in a geospatial environment.

2.1. The GNSS integrity module

RAIM algorithms are able to provide PLs, defining a region of the space which includes the true receiver position with a fixed probability; in particular, HPL is the radius of a circle, which contains the true horizontal position with defined probabilities of false alert and missed detection. The most widespread computation of HPL from RAIM is detailed in (Brown & Chin, 1997), where HPL expression is:

$$HPL = MDB * Slope_{max}$$

MDB is the minimum detectable bias and depends on the probabilities of false alarm and missed detection, on the measurement redundancy (i.e. the difference between number of measurements and unknowns), and on the measurement uncertainty.

The “slope” is defined as the ratio between the horizontal position error and the magnitude of the residuals, assuming the absence of noise and the presence of a bias affecting only one measurement. $Slope_{max}$ is the maximum slope and it is associated with the most insidious measurement, for which a low residual corresponds to a large position error. Such parameter depends only on the design matrix of the equations system, in turn related to the receiver-satellites geometry.

The design matrix can be expressed in terms of elevation and azimuth of the satellites with respect to receiver; naming El_i and Az_i respectively the elevation and the azimuth of the i^{th} satellite, the design matrix H can be expressed as:

$$H = \begin{bmatrix} & & \cdots & \\ -\cos El_i * \sin Az_i & -\cos El_i * \cos Az_i & -\sin El_i & 1 \\ & & \cdots & \end{bmatrix}$$

The size of matrix H is mx4, with m number of available satellites and 4 number of unknowns in GPS-only case.

2.2. The structure of the real-time WebGIS platform

The developed framework was based on the integration of a low-cost GNSS acquisition device, a Python-based integrity computation module, a PostgreSQL database, and a WebGIS visualization environment (**Fig.2**). Unlike the preliminary prototype based on a dedicated Mini NEO-6M GNSS board, the experimental campaign presented in this paper employed a commercial Android smartphone acting as a multi-constellation GNSS receiver.

The smartphone used during the experiment was a Xiaomi 11T device running Android 15. The embedded GNSS chipset was able to simultaneously track signals from multiple satellite constellations, including GPS, Galileo, GLONASS, and BeiDou. The developed platform allowed us to export in real-time GNSS observations using the open-source application GPS NMEA Tether, which allowed the transmission of National Marine Electronics Association (NMEA) messages from the smartphone to the processing workstation through a local Bluetooth Serial Port Profile (SPP) connection.

The transmitted NMEA stream included standard GNSS sentences such as GGA, RMC, GSA and GSV. These messages provided real-time information about receiver coordinates, satellite geometry, signal quality indicators and satellite visibility. The communication between the smartphone and the workstation was established through a local wireless network, avoiding the need for dedicated GNSS hardware interfaces.

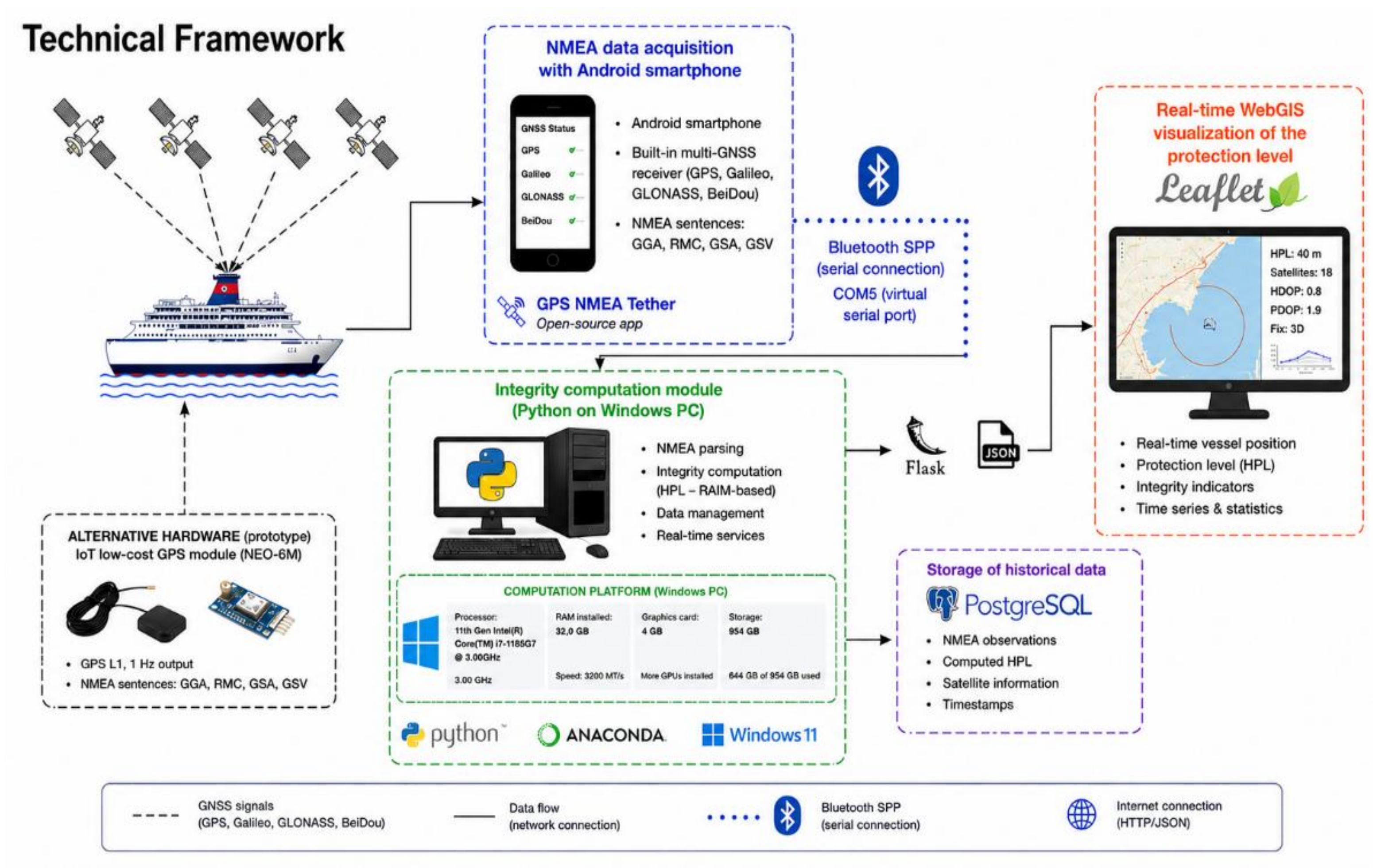

Fig. 2. All the software and hardware components involved in the platform.

The integrity computation module was executed within an Anaconda Python environment running on a Windows 11 Pro workstation equipped with an 11th Generation Intel® Core™ i7-1185G7 processor operating at 3.00 GHz, 32 GB of RAM, a 4 GB graphics card, and a 954 GB SSD storage unit. The module continuously received NMEA observations from the smartphone, extracted the information required for the integrity analysis, and computed the Horizontal Protection Level (HPL) at a frequency of 1 Hz. Flask open-source libraries were employed to expose the integrity results through JavaScript Object Notation (JSON) services, while the psycopg2 adapter was used to store historical observations within a PostgreSQL database.

The processing workstation communicated with an Apache web server hosting the WebGIS visualization environment. The WebGIS interface was developed using Leaflet open-source JavaScript libraries and was designed to provide real-time visualization of the vessel position and the associated Horizontal Protection Level. The HPL was represented as a circle centred on the vessel position, while historical observations were stored and queried from PostgreSQL.

The complete architecture was entirely based on open-source technologies, including Android 15 GNSS utilities, GPS NMEA Tether 1.1.0, Python 3.12, Flask 3.1.3, PostgreSQL 18.1, Apache Web Server 2.0, and Leaflet 1.9.4 libraries. This approach allowed the development of a low-cost digital twinning framework suitable for real-time coastal navigation monitoring without requiring professional maritime GNSS infrastructures.

2.3. Experimental dataset

A real-world navigation experiment was conducted to evaluate the operational capabilities of the proposed GNSS integrity framework. The test was performed aboard a ferry operating along the Strait of Messina. During the navigation, GNSS observations were continuously acquired using the Android smartphone described in Section 2.2. The system allowed the real-time transmission of NMEA information to the integrity computation module through the GPS NMEA Tether application.

The acquisition system generated standard NMEA 0183 messages, including GGA, RMC, GSA, and GSV sentences, at a nominal frequency of 1 Hz. The resulting NMEA stream was processed in real-time by the Python-based integrity module and simultaneously stored within the PostgreSQL database for subsequent analyses. The experiment produced 1,877 valid GNSS epochs collected over a period of 31 minutes and 17 seconds. The navigation scenario included both harbour manoeuvres and open-water navigation conditions, providing a representative dataset for evaluating the behaviour of the proposed integrity framework under realistic maritime operational conditions.

Table 1 summarizes the main characteristics of the experimental dataset used for the validation of the proposed architecture.

Table 1.

The experimental navigation dataset.

Parameter	**Value**
Navigation scenario	ferry navigation
Acquisition date	18 June 2026
Acquisition duration	31 min 17 s
Acquisition frequency	1 Hz
Valid GNSS epochs	1,877
GNSS receiver	Android smartphone (Xiaomi 11T)
Android version	Android 15
Data transmission	Bluetooth SPP connection
Transmission software	GPS NMEA Tether
NMEA protocol	NMEA 0183
Available messages	GGA, RMC, GSA, GSV
Processing platform	Python (Anaconda) on Windows 11
Database	PostgreSQL
WebGIS framework	Leaflet

3. RESULTS

The functionalities of the proposed platform were validated through a real-world maritime navigation experiment conducted aboard a ferry operating between Villa San Giovanni and Messina (Italy). During the navigation, GNSS observations, acquired by an Android smartphone, were transmitted and the platform enabled the dynamic Bluetooth SPP connection to the integrity computation module implemented in Python within the Anaconda environment. The incoming NMEA stream was processed at a frequency of 1 Hz, allowing the continuous computation of the Horizontal Protection Level (HPL), satellite geometry indicators, and navigation quality parameters.

The processed information was remotely visualized through a WebGIS platform developed using Leaflet JavaScript libraries (**Fig. 3**).

The interface provided a real-time representation of the vessel position together with the associated protection level. The current HPL was displayed as a circle centred on the vessel position, whose radius was dynamically updated according to the integrity computation results. In addition, the platform continuously generated and displayed the complete navigation trajectory, allowing users to monitor both the current position and the historical evolution of the route.

The WebGIS interface was further enhanced by integrating real-time quality indicators derived from the GNSS observations. In particular, the Horizontal Dilution of Precision (HDOP), Position Dilution of Precision (PDOP), number of available satellites, and HPL values were continuously updated during the navigation and made available to the end user. This information provided an immediate assessment of both positioning geometry and navigation integrity conditions.

Simultaneously, all observations and integrity indicators were archived within a PostgreSQL database. The historical acquisition component enabled the visualization and retrieval of previously processed observations, supporting post-processing analyses and integrity performance assessment. The complete acquisition-processing-storage-visualization chain operated continuously throughout the experiment, demonstrating the capability of the proposed architecture to support dynamic integrity monitoring under actual maritime navigation conditions.

The map was automatically centred on the vessel position according to the update frequency of the navigation solution, allowing continuous visualization of the navigation scenario. The flexibility of the Leaflet environment also enables the future integration of additional geospatial layers and external geospatial services, including OGC-compliant Web Map Services (WMS) and Digital Twin components. The adoption of exclusively open-source technologies allowed the implementation of the complete framework without licensing costs, improving its reproducibility and facilitating future developments for low-cost maritime navigation monitoring applications.

The proposed framework was evaluated through a real-world navigation experiment conducted aboard a ferry operating between Villa San Giovanni and Messina. **Fig. 4** reports the temporal evolution of the Horizontal Protection Level (HPL), Horizontal Dilution of Precision (HDOP), and Position Dilution of Precision (PDOP) computed from the acquired NMEA observations. The HPL values were derived according to the RAIM-inspired methodology described in Section 2, based on the SLOPE parameter computed from the satellite geometry matrix and the adopted pseudorange standard deviation.

The obtained results highlight the overall stability of the GNSS geometry during the entire navigation experiment. HDOP values remained consistently below 1.0, with an average value close to 0.5, while PDOP values were generally lower than 1.5. Such indicators denote favourable satellite visibility conditions and a well-conditioned positioning geometry throughout the navigation route.

The computed HPL exhibited limited fluctuations along the trajectory, with average values of approximately 35 m and maximum peaks below 85 m. The observed variations were mainly associated with changes in satellite geometry related to modifications in constellation visibility occurring during different phases of the navigation. Nevertheless, no significant degradation of integrity performance was detected, and the HPL remained within a relatively narrow operational range for the entire duration of the experiment.

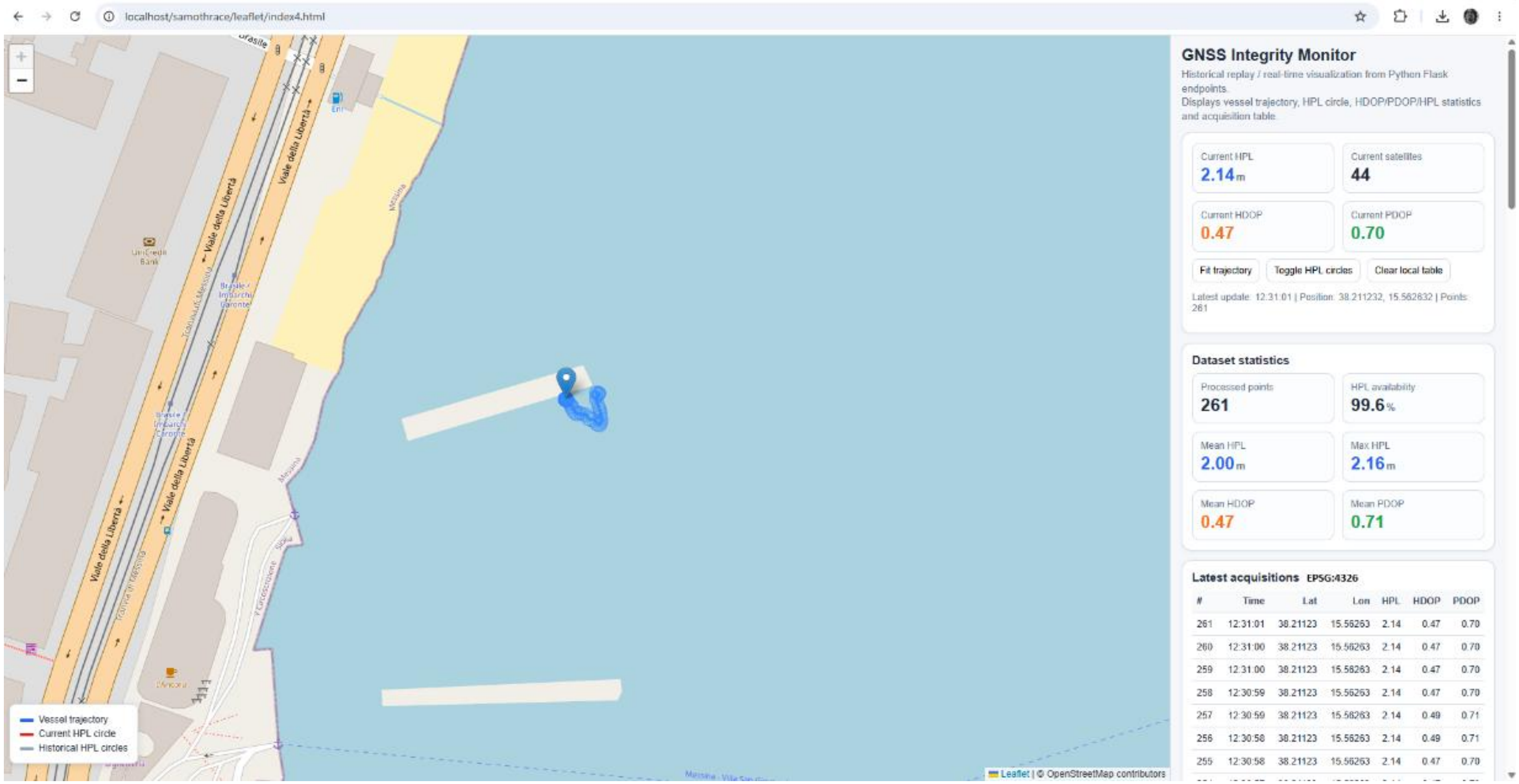

Fig. 3. Real-time WebGIS visualization of the proposed integrity monitoring framework. The interface displays the vessel trajectory, the current Horizontal Protection Level (HPL) represented by the blue protection circle, and the real-time integrity indicators (HDOP, PDOP, satellite availability, and HPL statistics) derived from the GNSS observations acquired during the Villa San Giovanni –Messina navigation experiment in WGS84 – EPSG:4326 .

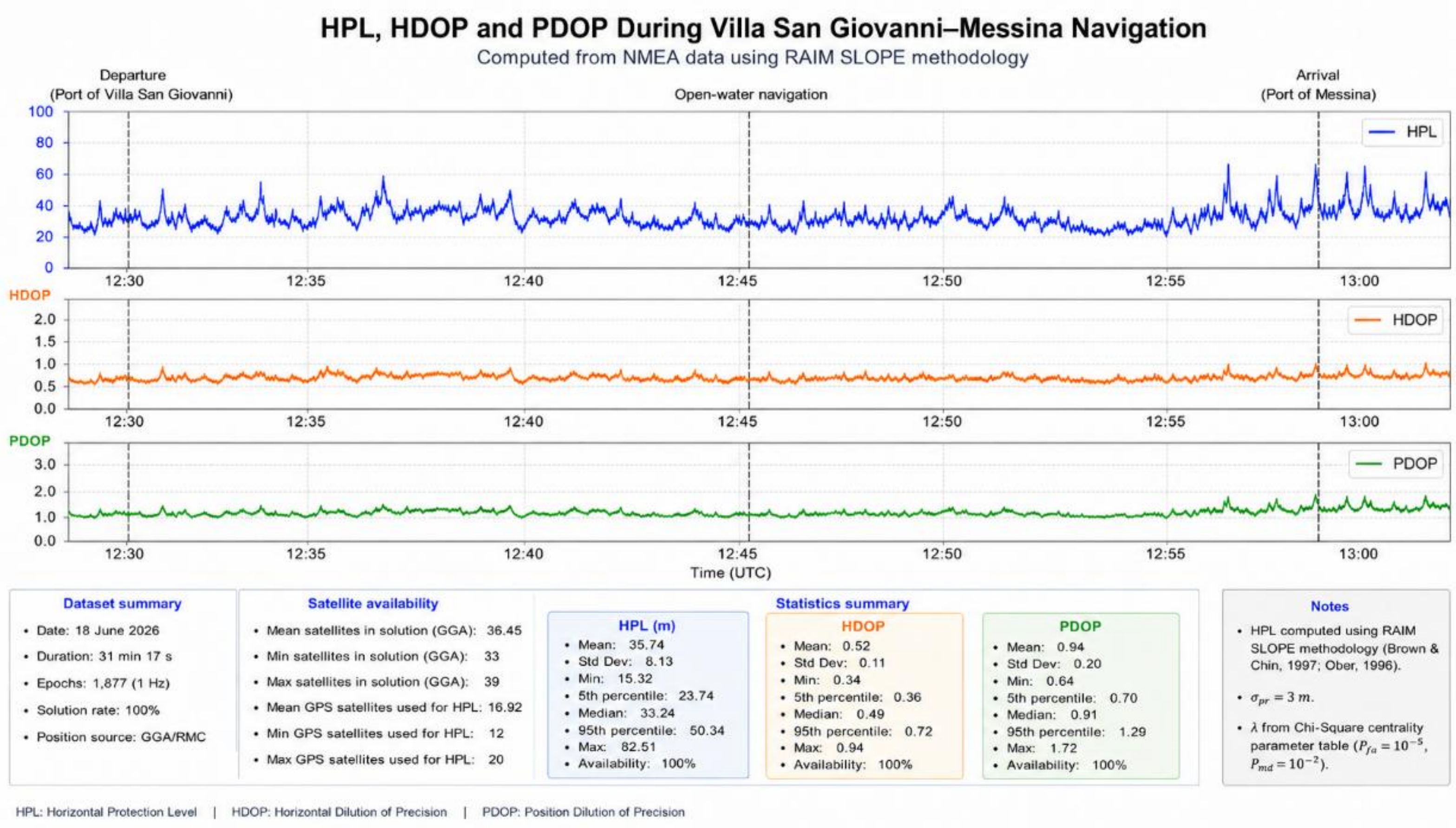

Fig. 4. The timeline of HPL, HDOP, PDOP trend during the test of navigation.

4. DISCUSSION

The real-time tracking of ships using GNSS and WebGIS together represents useful technology for the real-time monitoring of boating activities (Yen et al., 2009). Recent applications considered also the integration of low-cost bathymetric acquisition to extract ship motion data and correct depths in dynamic shallow water systems (Bio et al., 2020). In our case, the proposed solution integrates the real-time visualization of the horizontal protection level, which contains the estimated horizontal position of the ship, into a WebGIS platform.

The entire structure is developed using low-cost GNSS hardware equipment and open-source software solutions to provide an instrument widely suitable for municipalities and private companies. Although the proposed framework demonstrated stable behaviour during the real navigation experiment, the validation presented in this work was intentionally focused on assessing the feasibility of the complete real-time integrity monitoring architecture rather than on benchmarking positioning performance against professional maritime GNSS equipment. A comparison with geodetic-grade or certified maritime GNSS receivers would allow a more rigorous assessment of both positioning accuracy and the computed Horizontal Protection Level (HPL). Such an experimental campaign was outside the scope of the present work due to the unavailability of professional reference instrumentation during the navigation tests. Nevertheless, the developed platform has been specifically designed to be hardware-independent, making future comparative experiments with professional GNSS receivers straightforward without requiring modifications to the integrity computation or WebGIS architecture.

Considering the economic impact of the framework, the costs are limited to the low cost GNSS receiver. In fact, the platform employs only open-source technology compliant with Windows, Linux, and macOS (Apple), using the Anaconda platform for Python computation, the PostgreSQL database for the storage of position information, and Leaflet JavaScript libraries for the WebGIS design.

If on the one hand the opensource nature of the platform allows the spread of the application, on the other hand it requires programming skills for developing and integrating the different modules that compose its structure (low cost GNSS module, Integrity computation module, Database, real-time WebGIS visualization). Another challenge is the limitation of use to coastal navigation due to the need for data transmission over the 4G network between the integrity calculation module and the WebGIS+database structure.

However, it is necessary to underline that this kind of application is very useful for coastal navigation due to the intensive traffic of ships that characterizes the harbors and their neighborhoods where a valid integrity computation can be precious especially in adverse weather conditions.

Similar recent experimentations were considered for the development of vehicle live tracking systems for public transport in urban areas (Amer et al., 2024), or for real-time metro rail localization (Aggarwal et al., 2023) allowing a WebGIS real-time visualization of GPS integrity location data based on Flutter Google open-source framework. These solutions are compliant with iOS and Android platforms and represent a valid possibility if we want the implementation of the platform in a mobile application instead of a web browser navigation.

An interesting aspect emerging from the analysis is the correspondence between local increases in HDOP/PDOP and the occurrence of higher HPL values. This behaviour is consistent with the adopted integrity model, since both dilution of precision indicators and protection levels are directly influenced by the underlying satellite geometry. The results therefore confirm the capability of the proposed framework to dynamically reflect changes in GNSS observation conditions and to provide meaningful integrity information to the end user.

The experiment also demonstrated the operational robustness of the complete acquisition-processing-storage-visualization chain. During the 31-minute navigation campaign, 1,877 valid GNSS epochs were processed without interruptions, achieving continuous integrity monitoring, real-time WebGIS dissemination, and persistent storage of all navigation observations within the PostgreSQL database. These results validate the feasibility of employing low-cost commercial devices and open-source software components for real-time maritime integrity monitoring applications.

In fact, the main contribution of this research is not limited to the implementation of a GNSS integrity algorithm but consists in the development and validation of a complete real-time open-source framework that seamlessly integrates GNSS acquisition, integrity computation, database management, and WebGIS dissemination within a unified Digital Twin-oriented architecture for maritime navigation.

5. CONCLUSIONS AND OPEN SCENARIOS

This work presented a low-cost open-source framework for real-time GNSS integrity monitoring and WebGIS visualization designed for coastal maritime navigation. The proposed architecture integrates commercial GNSS hardware, Python-based integrity computation, PostgreSQL data storage, and a WebGIS dashboard developed with open-source technologies, providing a complete acquisition-processing-storage-visualization workflow.

The experimental validation was performed during a real navigation campaign aboard a ferry operating between Villa San Giovanni and Messina (Italy). GNSS observations were continuously acquired using an Android smartphone and transmitted through a local Bluetooth SPP connection to the integrity computation module. The developed framework successfully computed the Horizontal Protection Level (HPL) at a frequency of 1 Hz while simultaneously storing all observations within a PostgreSQL database and publishing the integrity information through the WebGIS interface. The experimental results demonstrated the operational stability of the proposed architecture during the entire navigation, confirming the capability of the framework to support continuous integrity monitoring under realistic maritime conditions.

Compared with the preliminary prototype, the developed platform provides a significantly enhanced monitoring environment. In addition to the real-time visualization of the protection level, the WebGIS now integrates the complete vessel trajectory together with navigation quality indicators such as HDOP, PDOP, satellite availability, and historical integrity statistics. These functionalities transform the WebGIS from a simple visualization interface into an operational integrity monitoring dashboard capable of supporting both real-time situational awareness and post-processing analyses.

The exclusive adoption of open-source software components considerably reduces implementation and maintenance costs, making the proposed solution suitable for research activities, public administrations, and private organizations interested in developing low-cost Digital Twin applications for maritime navigation. Although the current implementation focuses on coastal navigation scenarios, the modular architecture allows straightforward integration with additional geospatial services, IoT sensors, and external environmental information.

Future developments will focus on extending the integrity computation to full multi-constellation GNSS processing, integrating additional navigation and environmental sensors, and implementing satellite communication technologies to remove dependency on terrestrial wireless networks during offshore navigation. Furthermore, future research will investigate the integration of predictive integrity models and Digital Twin functionalities capable of supporting decision-making processes through continuous monitoring and forecasting of navigation conditions.

To encourage reproducibility and further developments by the scientific community, a demonstration version of the developed framework is publicly available at: https://github.com/marcellolg1987/realtime_PL_WebGIS_analyzer.

Another promising research direction concerns interoperability with emerging geospatial IoT standards. Although the current implementation relies on lightweight JSON services for real-time communication, future versions of the framework will investigate the adoption of OGC SensorThings API to standardize the management and dissemination of GNSS observations and integrity indicators. Such an evolution would facilitate interoperability with heterogeneous sensor networks, Digital Twin platforms, and Smart City infrastructures, while improving scalability and compliance with internationally recognized geospatial standards

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