GIN Project: A Geodetic Integrated Network for Monitoring and Topographical Surveying in the Emilia-Romagna Region Suitable both for Classical and Space Geodetic Techniques

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Abstract

Geodetic networks are fundamental for the representation, monitoring, and management of territory. The network of permanent GNSS stations and the tide gauge networks enable the accurate definition and monitoring of the reference system, addressing both spatial and altimetric aspects (with the availability of both ellipsoidal and orthometric heights). Passive networks, used for three-dimensional positioning (via GNSS or traditional topographic instruments) or for altimetric measurements, allow comprehensive access to all parts of the territory and support more localized surveys. The Emilia-Romagna region in Italy is a territory affected by subsidence (both natural and anthropogenic), coastal erosion, landslides, and recent catastrophic events such as earthquakes and extreme weather phenomena. To effectively manage and monitor such a complex territory, relevant authorities have developed an Integrated Geodetic Network project, comprising permanent GNSS stations (capable of providing real-time positioning services), tide gauges, and passive networks referenced to shared coordinate systems. With the support of a geoid undulation model, this system will enable more accurate understanding and management of the territory.

Keywords

Geodetic network · Geometric levelling · GNSS · Reference frame · Tide gauges

1 Introduction

The Emilia-Romagna Region is largely characterized by the alluvial plain of the Po Valley, bordered to the southwest by the northern Apennines. Its coastline, primarily sandy, extends for over 120 km along the Adriatic Sea. The region is one of the most industrialized and densely populated areas of Italy and, in recent years, its territory has been affected by severe natural events, causing numerous fatalities. Notably, the 2012 earthquake caused extensive damage to buildings

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and infrastructures, while extreme rainfall events in 2023 and 2024 resulted in widespread flooding and landslides. Additionally, the Po Valley is affected by natural subsidence, which in some areas is exacerbated by anthropogenic activities. This phenomenon alters local slopes and contributes to hydraulic problems. The Apennines are highly prone to landslides, while coastal areas experience sand erosion, reducing the natural defences against extreme marine events coming from the sea. Therefore, Emilia-Romagna can be considered as a fragile and dynamically evolving territory, requiring continuous monitoring. To manage this complexity, the regional public administration collaborates closely with specialized working groups and maintains strong links with Civil Protection, land Reclamation Consortia, and Basin Authorities of the main regional rivers. These authorities require accurate, up-to-date geo-topographic data to understand and monitor the territory and its evolution. The following sections illustrate: (1) the main requirements and underlying motivations that led the Emilia-Romagna public administration to develop a Geodetic Integrated Network (GIN) project with regional coverage; (2) the conceptual framework and implementation strategy of the GIN project; and (3) the current progress of the works.

2 Context and Stakeholders Needs

2.1 Real Time Precise Positioning for Technical Applications

Current National regulations assign each regional authority the responsibility of maintaining up-to-date topographic maps and databases. The regional geodetic Reference System forms the foundation for these activities, with an operational unit fully dedicated to its maintenance. Public spatial data are currently updated in various ways, including high-resolution satellite imagery and aerial photogrammetry. Therefore, geodetic networks are essential for properly georeferencing these products, facilitating the updating of topographic databases and related cartographic materials. Within Emilia-Romagna, numerous organizations operate in the territory, including Reclamation Consortia, River Basin Authorities, Civil Protection, and municipalities. Recently, precision agriculture has also emerged as an increasingly important field. For these reasons, two geodetic infrastructures to support these activities are required. The first is a network of permanent GNSS stations providing real-time correction services with centimeter-level accuracy, supporting all operators exploiting this technology. The second is a denser network of surveying benchmarks, serving as reference points for those employing traditional surveying techniques or GNSS in RTK mode. Both networks must be referenced to a common reference system. Additionally, a geoid undulation model is required, and the passive network must include precise orthometric heights for all points.

2.2 Coastal Erosion

The coastal area of Emilia-Romagna is characterized by a low, sandy beach stretching 120 km (Emilia-Romagna 2020). This area is exposed to marine ingression, beach erosion, and subsidence. Since the 1980s, the regional administration has implemented coastal defense measures, including breakwaters, groins, seawalls, and beach nourishments, to protect low-lying areas, in some cases below the sea level, from marine action. At the same time, the Environmental Agency (now Arpae) has monitored the evolution of erosion processes and the effectiveness of defence interventions through topographic and bathymetric surveys of both emerged and submerged beaches. A robust geodetic framework is essential for these surveys, requiring benchmarks along the coastline with known orthometric and ellipsoidal heights and permanent GNSS stations for satellite-based measurements. Furthermore, with the aim of monitoring and protecting the coastline, it is essential to define a mean local sea level and to monitor its temporal variation through tide gauge stations distributed along the regional coast.

2.3 Coastal Hydrography and Rivers Monitoring

Many regional rivers are equipped with hydrometric stations designed to constantly measure water levels relative to their respective hydrometric zeros. However, these zeros are not consistently defined, as each is relative to the elevations of the riverbed and levees at the specific location of the hydrometric station. This complicates flood dynamics analysis and accurate hydraulic modelling, particularly in the predominantly flat areas of the region. To address this, a unified levelling network is necessary to connect the hydrometric stations and relate them to both riverbed and levee elevations along the upstream-downstream profile and to the sea level, measured by tide gauges along the coast within a consistent reference system.

2.4 Subsidence Monitoring

Emilia-Romagna Plain is affected by natural subsidence, estimated at a few millimetres per year, caused by the compaction of sediments from alluvial deposits. Since the 1950s, anthropogenic subsidence due to subsurface fluid extraction has also occurred (Nespoli et al. 2021). In areas where the phenomenon was most pronounced, multiple subsidence monitoring networks were established, but, in a regional con-

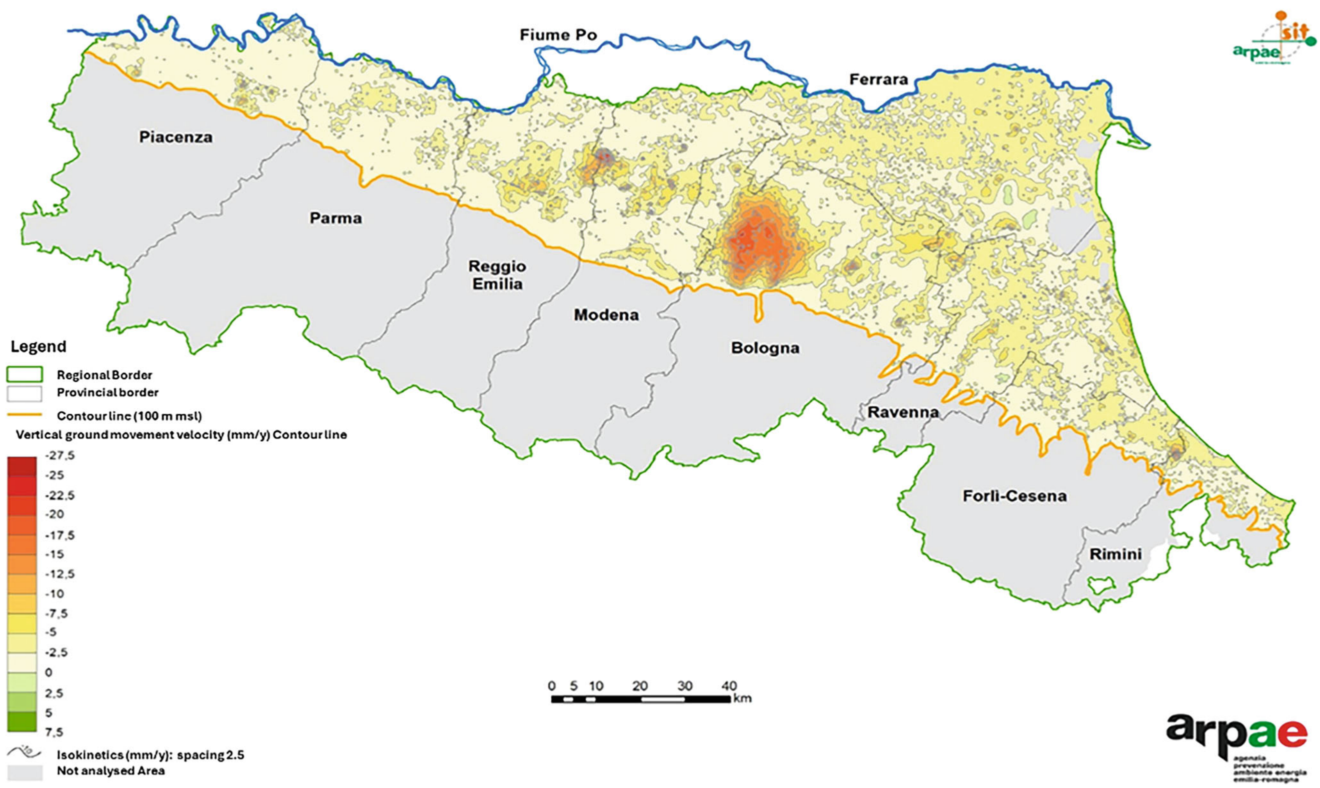

Fig. 1 Map of vertical ground motion velocities in Emilia-Romagna—Italy (2016–2021 period)

text, they suffered from overlaps, gaps, and inhomogeneities. Starting in 1997–1998, under the commission of the Region, the Emilia-Romagna Environmental Agency (Arpae) established a regional subsidence monitoring network in the plain area, consisting of 2,300 corner point stations and 60 GPS stations, with levelling measurements conducted at 5-year intervals (Bitelli et al. 2000; Bissoli et al. 2012). In the last 20 years, satellite-based monitoring has increased precision and coverage. Indeed, the most recent update of the subsidence monitoring dataset (2016–2021) used interferometric analysis of satellite radar data (SqueeSAR™) with double geometry (Marcaccio and Mazzei 2023). Calibration of vertical and horizontal ground movement components with data from permanent GNSS stations enabled the creation of isokinetic maps of vertical motion with 2.5 mm/year resolution (Fig. 1). A periodically updated geometric levelling network, including GNSS stations, is essential for calibrating SAR data and monitoring vertical ground movements in areas of low SAR coverage.

2.5 Marine Forecasting Modelling

Understanding coastal dynamics and supporting marine forecasting models requires the development of a comprehensive tide gauge network for sea-level monitoring. Additionally, the presence of co-located GNSS permanent stations could enable the detection of both sea level variations and local vertical land movements, including subsidence, ensuring accurate long-term observations (Becker et al. 2002; Wöppelmann et al. 2006).

In this context, performing high precision levelling measurements would align all stations to a single vertical datum, ensuring consistent sea-level measurements along the coastline. Scientific analysis, coastal management, climate change adaptation strategies, and the planning of coastal and maritime infrastructures all could benefit from this integrated approach, which enhances the reliability of the data.

3 The GIN Project

Currently, Italy maintains passive levelling and 3D geodetic networks, managed by the Italian Military Geographic Institute. Although passive networks can offer high point density, they are limited by the requirement to periodically update coordinates. Indeed, for these networks, heights are currently referenced to the Genoa tide gauge (mean sea level Genoa 1942), and horizontal coordinates use the ETRF2000—epoch 2008.0 realization of the ETRS89 reference system. Given the complexity of the Emilia-Romagna region, this geodetic infrastructure does not fully meet local administrative needs, as the coordinates do not account for processes such as natural and anthropogenic subsidence, landslides, coastal erosion, and, more recently, extreme meteorological events. Furthermore, knowledge of the current local mean sea level is important for coastal protection and climate change monitoring.

In response to regional monitoring and management needs, the GIN project was proposed and has been developed by the main groups involved in surveying and monitoring the Emilia-Romagna territory. The project addresses key objectives as described in Sect. 2. The initiative recognized the necessity of different networks of geodetic benchmarks with precise orthometric and ellipsoidal heights, supported by permanent GNSS stations and co-located tide gauges, to ensure reliable and long-term measurements.

Indeed, the GIN project integrates active sensors (GNSS permanent stations and tide gauges) with passive geodetic networks with benchmarks for altimetric control (through geometric levelling) and 3D surveying (through GNSS).

This continuously monitored geodetic infrastructure provides a unified reference for data collection and analysis. It enables synergistic operations among multiple agencies, facilitating effective territorial monitoring, disaster mitigation planning, and coordination between public administrations, scientific institutions, and field operators.

The diagram in Fig. 2 details the structure of the GIN, divided into active and passive components.

GNSS permanent station networks enable real-time surveys with centimeter-level precision (NRTK), calibration of subsidence maps obtained via InSAR interferometry, and allow accurate framing of traditional networks for technicians and surveyors performing cartographic updates.

Tide Gauges co-located with GNSS permanent stations, improve the understanding of sea dynamics and storm surges forecasting and allow isolating subsidence effects to accurately assess mean sea-level rise and allow the definition of a regional mean sea level to be related to the national reference.

Passive Networks (Level 2) (altimetric and planimetric) will support Basin Authorities, Reclamation Consortia, Municipalities, Public Bodies, and Private operators by providing a precise, shared reference system (and frame), thus facilitating data sharing.

4 Technical Aspects of the GIN Project

One of the key elements of the GIN project, carefully addressed during the design phase, is the integration of its various components to ensure that all the aforementioned requirements are expressed within a consistent planimetric and altimetric geodetic reference system. The main technical aspects considered include:

- a network of GNSS stations covering the entire regional territory;
- tide gauges connected through geometric levelling;
- a levelling network extending inland from the coast across the subsidence-prone plain territory, with lines following the main river courses;
- GNSS stations co-located with tide gauges;
- passive network points located near GNSS permanent stations;
- passive GNSS points coinciding with levelling benchmarks;
- levelling benchmarks positioned in proximity to hydrometric gauges.

The geodetic network will be aligned with the ETRF2000 (epoch 2008.0), Italy's official reference since 2009. Benchmark elevations will be referenced to coastal tide gauges for local mean sea level and connected to the national height datum at Genoa 1942. The elevation updates will incorporate subsidence models provided by Arpae. The newest ITALGEO (Barzaghi et al. 2007) geoid model will be locally adapted using observations from the new regional benchmarks.

5 Geodetic Network Design and Current State of Implementation

This section provides a brief overview of the GIN project components (Fig. 3) and their current state of implementation (Fig. 4).

5.1 Tide Gauges and Coastal Levelling Line

Two new tide gauges have been installed in Cervia and Cattolica, complementing existing tide gauges in Porto Garibaldi, Marina di Ravenna (ISPRA) and Faro di Goro (blue star symbol in Figs. 3 and 4). Porto Garibaldi, Cervia, Marina di Ravenna and Cattolica stations are co-located with permanent GNSS stations. In particular, the Porto Garibaldi GNSS station, as part of the EUREF permanent GNSS network since 2009, provides local mean sea level data (from 2010 to today) adjusted for subsidence, referred to international and national geodetic systems. Starting from the Porto Garibaldi station, in 2023, a high-precision coastal levelling line was established, within the GIN project, connecting all tide gauges and 67 benchmarks along the

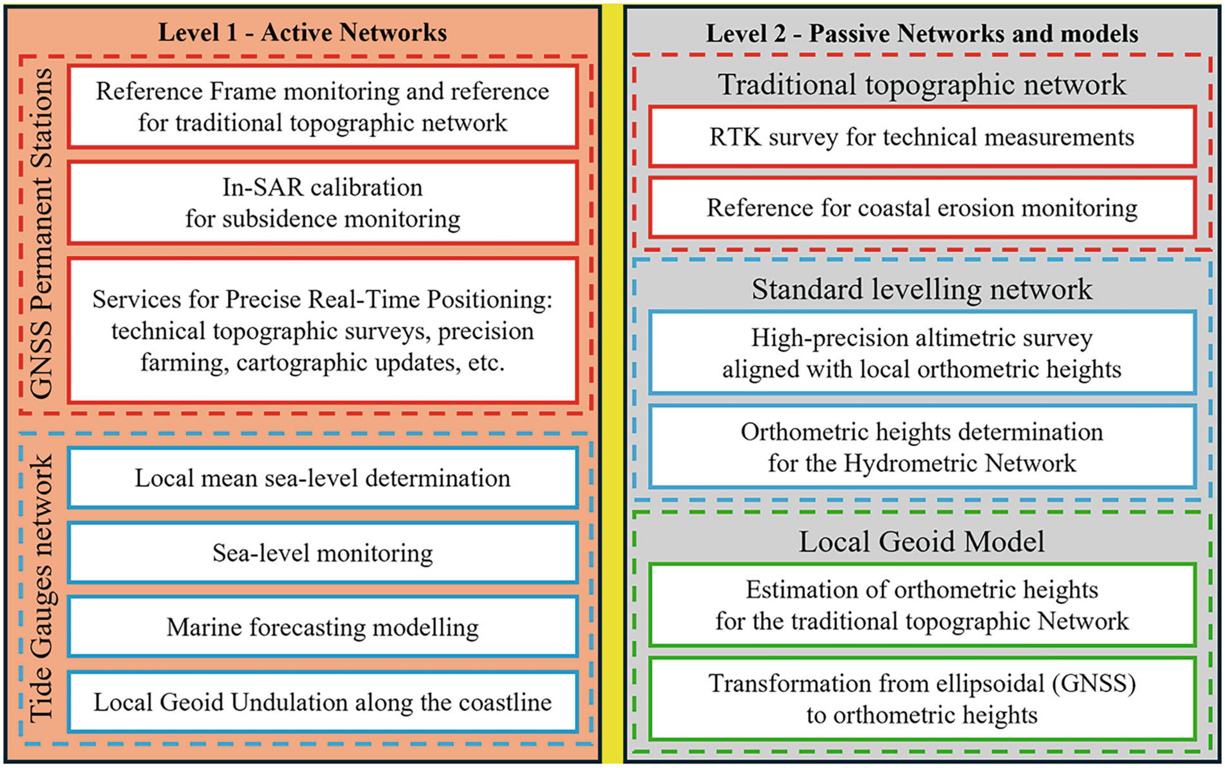

Fig. 2 Logical scheme of the Active Network and Passive Networks inside GIN

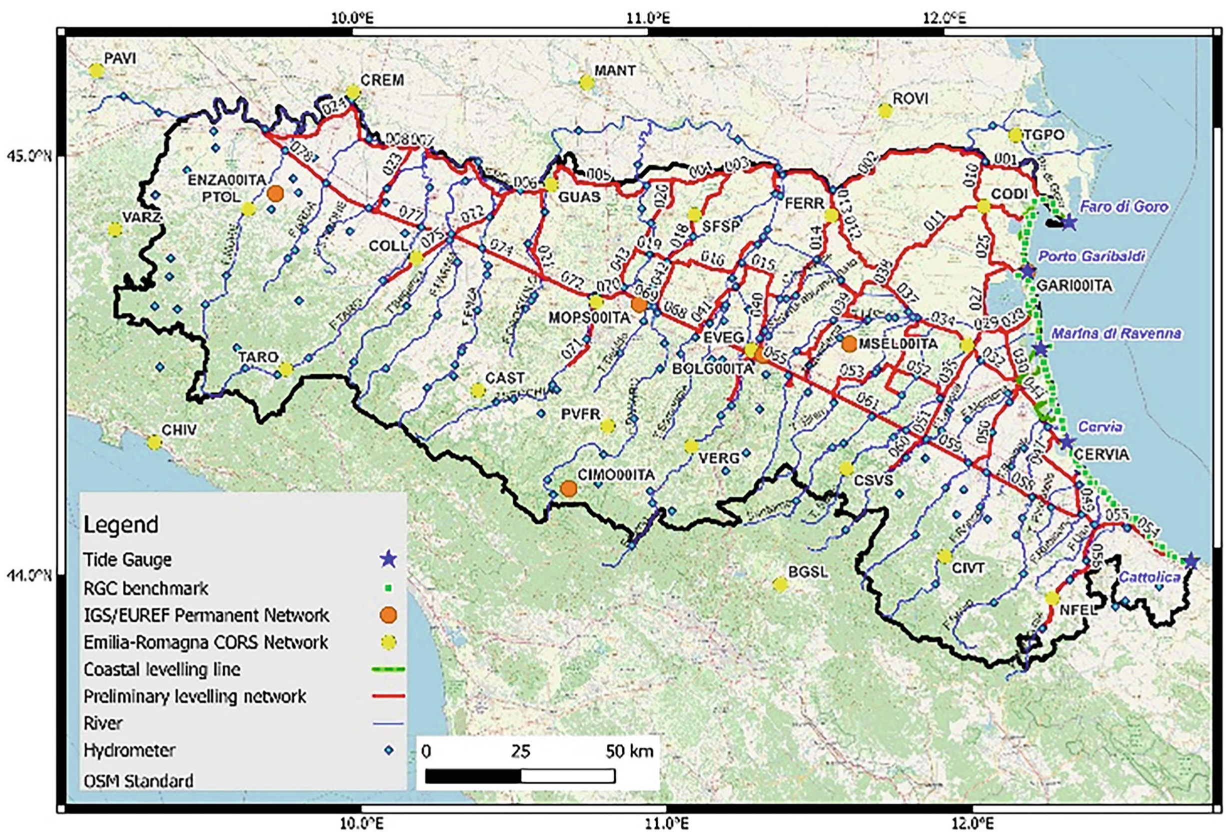

Fig. 3 Design of the Geodetic Integrated Network (GIN)

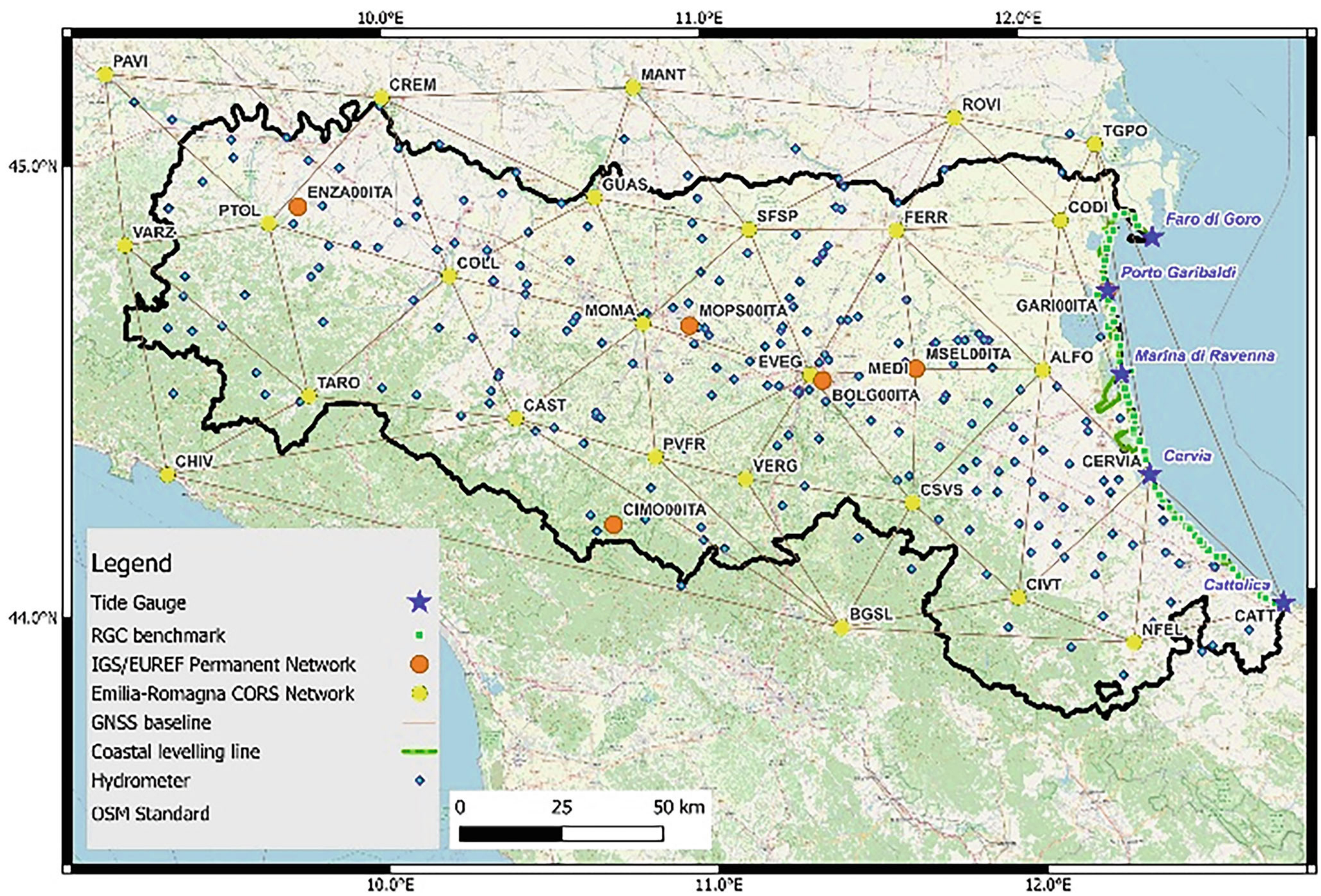

Fig. 4 Current status of the GIN project implementation

coastline (called RGC: Rete Geodetica Costiera, Coastal Geodetic Network, with a green square symbol in Figs. 3 and 4). This network serves as a reference for monitoring coastal erosion and for the construction of defence structures.

5.2 High-Precision Geometric Levelling and Hydrographic Network

The GIN project aims to integrate the Emilia-Romagna coastline and inland territory into a high-precision geometric levelling network. In summary, the network will consist of approximately 1,518 km of levelling lines (double-run), organized in 27 closed rings, with an average section length of 1 km (red line in Fig. 3). The levelling lines have been designed to create altimetric connections between the 86 telehydrometers already installed in the plains and hills along the main hydrographic network (blue diamond in Figs. 3 and 4). As a result, all water level values within the hydrographic network will be referenced to a unified altimetric system connected to the local mean sea level of Porto Garibaldi.

5.3 CORS GNSS Network

Within the GIN project, the Continuously Operating Reference GNSS Stations (CORS) network is already in the installation phase. The CORS network consists of 69 GNSS stations (including the stations on the coast of Cervia and Cattolica co-located with the tide gauges), with an average distance (baseline length) of about 40 km (yellow dot in Figs. 3 and 4).

5.4 Passive GNSS 3D Points

The GIN project foresees, as its final phase, the measurement of 3D GNSS passive points, covering the entire regional territory: this involves approximately 700 vertices, with an interdistance of approximately 7–10 km (not shown for graphical reasons in Figs. 3 and 4). These vertices will be chosen as close as possible to the levelling benchmarks, or in their immediate vicinity, to facilitate altimetric connection. Knowing the ellipsoidal and orthometric heights of these

3D vertices allows the calculation of geoid undulation and the creation of a local geoid model for the conversion from ellipsoidal to pseudo-orthometric height, based on the GIN network.

5.5 Outlook

The completion of the GIN project will enable the availability of updated local geodetic systems, both planimetric and altimetric, across the regional territory, fully linked to the national references. These systems will ensure accurate monitoring of the territory and of the natural and anthropogenic phenomena affecting it and will serve as the fundamental reference for all topographic surveys.

The next phase of the GIN project, already under development, includes the implementation of procedures for the continuous updating of all its active and passive components: an essential requirement for any modern geodetic network.

Competing Interests The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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