Evaluating the Rover-Side Performance of a Low-Cost GNSS Station for High-Accuracy Positioning and ZTD Estimation

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Keywords: Low-Cost GNSS network, GNSS meteorology, Zenith Tropospheric Delays(ZTD), Precise Point Positioning , Open-source

Abstract

The densification of GNSS Continuously Operating Reference Station (CORS) networks in mountainous regions is constrained by the high cost of geodetic-grade equipment. Low-cost (LC) multi-frequency GNSS receivers offer a viable alternative, yet their performance in challenging high-altitude Alpine environments remains largely unexplored. This study evaluates the rover-side positioning performance and tropospheric delay estimation capability of a newly installed LC permanent station at Prali (2200 m elevation), in the Alpine region of Piedmont, Italy. The station, based on a u-blox ZED-F9P receiver with a broadband LC antenna and a Raspberry Pi computer, was assessed using Virtual Reference Station (VRS) corrections from the SPIN3 professional CORS network. Six independent two-hour RTK sessions across a full diurnal cycle were processed using RTKLIB in forward-only kinematic mode to emulate real-time conditions. Results demonstrate that the LC station achieves centimetre-level horizontal precision (8–11 mm) with fix rates up to 97% and time to first fix below 3 minutes under favourable conditions. A diurnal performance variability was observed and characterised across the six sessions. Zenith Tropospheric Delay estimation via CSRS-PPP with 92% fixed ambiguities yielded physically consistent values (mean ZTD = 1811 mm, ZWD = 41 mm), consistent with dry winter conditions at altitude. These results confirm that LC GNSS stations can deliver reliable centimetre-level positioning and meaningful tropospheric products in demanding Alpine environments, supporting their deployment for CORS network densification in regions where geodetic-grade infrastructure is economically or logistically prohibitive.

1. Introduction

Accurate and reliable Global Navigation Satellite System (GNSS) positioning underpins a wide range of modern applications, from precision agriculture and autonomous navigation to environmental monitoring, geodynamic studies, and public safety. Centimetre-level accuracy is routinely achieved through Real-Time Kinematic (RTK) and Network RTK (NRTK) techniques, which rely on correction data derived from dense networks of Continuously Operating Reference Stations (CORSs). However, the deployment and maintenance costs of geodetic-grade equipment—together with the need for stable power supply, robust data connectivity, and regular calibration—limit the spatial density of such networks, particularly in remote, topographically complex areas such as mountainous regions.

In recent years, the rapid development of low-cost (LC) multi-frequency, multi-constellation GNSS receivers has opened new possibilities for densifying existing reference networks at a fraction of the cost of traditional geodetic-grade installations (Hamza et al., 2024). Several studies have demonstrated that LC receivers, when combined with appropriate correction services, can achieve sub-decimetre to centimetre-level positioning accuracy in open-sky conditions (Hamza et al., 2024). Moreover, the feasibility of LC GNSS stations for producing high-quality Zenith Tropospheric Delay (ZTD) estimates—approaching the performance of geodetic-grade systems—has been confirmed in recent experimental work (Krietemeyer et al., 2020, Dabove and Bagheri, 2024, Bosser et al., 2024, Stepniak et al., 2022). The resilience of LC permanent stations under adverse ionospheric conditions has also been investigated, showing that while geomagnetic disturbances degrade positioning performance, LC stations can still maintain operational capability comparable to geodetic-grade equipment (Bagheri and Dabove, 2025). Community-driven initiatives such as the Centipede-RTK network (`https://centipede.fr/`) have further demonstrated the viability of large-scale, volunteer-maintained LC GNSS infrastructures for both positioning and atmospheric applications.

Despite these advances, the performance of LC GNSS stations in challenging Alpine environments—characterised by complex topography, reduced satellite visibility due to terrain obstructions, significant tropospheric variability with altitude, and limited infrastructure availability—remains insufficiently investigated. Most existing evaluations of LC receivers have been conducted in lowland or suburban settings, where satellite geometry and atmospheric conditions are more favourable. The behaviour of LC stations at elevations exceeding 2000 m, where the representativeness of standard tropospheric models is reduced by complex orography, large height differences to surrounding reference stations degrade network correction interpolation, and satellite visibility may be limited by terrain obstructions, requires dedicated assessment.

In the framework of the PAIN AND GAIN project, which aims to develop cost-efficient GNSS infrastructure for precise positioning and atmospheric monitoring in challenging environments, an initial study established and evaluated a hybrid

https://doi.org/10.5194/isprs-archives-XLIX-B5-2026-57-2026

CORS network combining LC and high-grade (HG) receivers in the Alpine region of Piedmont, Italy (Dabove and Bagheri, 2025). Building on this foundation, the present work advances the concept by focusing on the rover-side performance of a newly installed, fully LC permanent station located at Prali, in the upper Val Germanasca, at approximately 2200 m elevation. The station, based on a multi-frequency u-blox receiver paired with a LC antenna and a Raspberry Pi processing unit, was specifically deployed to assess whether LC hardware can deliver reliable positioning and atmospheric products in a demanding high-altitude environment. As a necessary prerequisite before integrating this station into the hybrid network managed by GNSMART 2 (`https://www.geopp.de/gnsmart/`), the present study first evaluates its performance (rover side) using Virtual Reference Station (VRS) corrections from the Interregional GNSS Positioning Service (SPIN3 GNSS, `https://www.spingnss.it/`). This approach establishes an upper-bound benchmark: if the LC receiver cannot achieve satisfactory results with corrections from a geodetic-grade network, further deployment within a hybrid or fully LC network would not be justified. The results presented here therefore represent a critical validation step, providing the evidence base for the progressive densification of the existing hybrid network with additional LC stations.

The evaluation follows a dual-purpose approach. First, the station is treated as a rover, receiving VRS corrections from SPIN3, and its kinematic positioning performance is assessed through six independent two-hour sessions distributed across the day. This experimental design emulates real-time rover connections and allows the characterisation of diurnal performance variability driven by ionospheric activity and satellite geometry. Key performance metrics include fix rate, time to first fix (TTFF), positioning precision, and the identification of unreliable fixed solutions as a reliability indicator. Second, the station's capability to estimate ZTD via Precise Point Positioning (PPP) is evaluated using precise satellite orbit and clock products, using the Canadian Spatial Reference System Precise Point Positioning service (CSRS-PPP, `https://webapp.csrs-scrs.nrcan-rncan.gc.ca/geod/tools-outils/ppp.php`).

By demonstrating the feasibility and quantifying the limitations of a LC GNSS station operating at high altitude within an existing professional network framework, this study provides the evidence base for the progressive deployment of additional LC stations aimed at densifying the existing hybrid network toward a fully LC configuration. This supports the long-term objectives of the PAIN AND GAIN project, enabling cost-efficient deployment of GNSS infrastructure in challenging environments and paving the way toward fully low-cost, real-time positioning and atmospheric monitoring networks.

The remainder of the paper is organised as follows: Section 2 describes the study area, station hardware, observation data, and processing methodology. Section 3 reports and discusses the results for both RTK positioning and ZTD estimation, and Section 4 summarises the main findings and outlines future work.

2. Data and Methodology

2.1 Study Area and Observation Data

The newly installed Prali LC GNSS permanent station is located in the upper Val Germanasca, in the Alpine region of Piedmont, Italy, at an approximate elevation of 2200 m. The condition of this newly installed station make Prali a representative and challenging test case for evaluating LC GNSS performance in high-altitude environments (Figure 1).

The hardware configuration consists of a u-blox ZED-F9P dual-frequency multi-GNSS receiver paired with a broadband LC antenna, supported by a Raspberry Pi single-board computer responsible for data management, real-time streaming, and local storage. A Power-over-Ethernet (PoE) communication module ensures stable and continuous network connectivity, while all components are hosted in a weather-resistant enclosure suitable for long-term field deployment (Figure 1). The total hardware cost of the station is below EUR 600, representing more than one order of magnitude reduction compared to a geodetic-grade installation.

Figure 1. The Prali LC GNSS station at approximately 2200 m elevation: (left) building with antenna mounted on a pole,(centre) detail of the LC antenna installation, (right) indoor hardware including the u-blox ZED-F9P receiver and Raspberry Pi in a weather-resistant enclosure (highlighted).

The Prali station is part of a broader hybrid CORS network developed within the PAIN AND GAIN project (Dabove and Bagheri, 2025), which integrates LC stations with existing Centipede-RTK community stations (`https://centipede.fr/`) and is centrally managed using GNSMART 2 (Figure 2). As a prerequisite before integrating Prali into this hybrid network, the present study evaluates its performance using Virtual Reference Station (VRS) corrections from the Interregional GNSS Positioning Service (SPIN3 GNSS, `https://www.spingnss.it/`), a geodetic-grade infrastructure operated by Regione Piemonte. The VRS was generated for the Prali location based on corrections interpolated from five surrounding SPIN3 reference stations, covering 24 February 2026 at a 1-second observation rate with full data completeness.

Continuous observations were collected at Prali over the full 24-hour period at 1-second sampling, with an average of 16–19 visible satellites.

2.2 Processing Strategy

2.2.1 RTK Positioning Assessment. The rover-side positioning performance was evaluated in post-processed kinematic mode using RTKLIB demo5 b34h, a version of RTKLIB optimized for low-cost GNSS receivers (`https://github.com/rinex20/RTKLIB-demo5`) with the SPIN3 VRS as the base station. Processing was performed in forward-only filter mode to emulate real-time conditions, where only past and current observations contribute to each solution epoch. The main processing parameters include: L1+L2/E5b dual-frequency observations from GPS, GLONASS, and Galileo; a 10° elevation mask; Saastamoinen tropospheric model; broadcast eph-

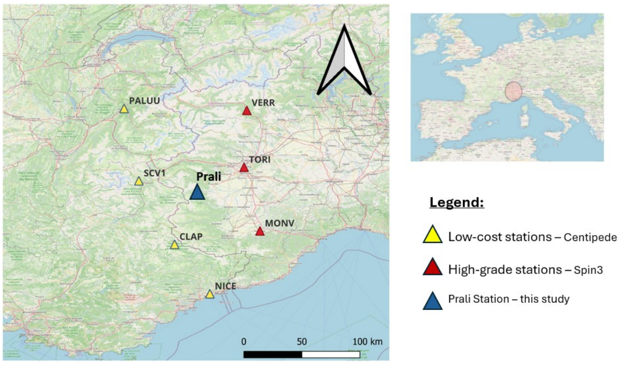

Figure 2. Prali station installed inside the previusly designed hybrid network at approximately 2200 m elevation. Yellow triangles: low-cost Centipede-RTK stations; red triangles: high-grade SPIN3 stations;

emerides; and Fix-and-Hold ambiguity resolution with a validation threshold of 3.0. The RTK configuration using RTKLIB demo5 b34h is summarized in Table 1

Parameter	Setting
Positioning mode	Kinematic
Filter direction	Forward
Frequencies	L1 + L2/E5b
Constellations	GPS + GLONASS + Galileo
Elevation mask	10°
Troposphere model	Saastamoinen
Ephemeris	Broadcast
Ambiguity resolution	Fix and Hold
Validation threshold	3.0

Table 1. RTKLIB processing configuration for the RTK evaluation.

To characterise diurnal performance variability, six independent two-hour sessions were processed, each simulating a separate rover connection: Night (00:00–02:00), Early morning (04:00–06:00), Morning (08:00–10:00), Midday (12:00–14:00), Afternoon (16:00–18:00), and Evening (20:00–22:00). The sessions are summarized in Table 2.

Session	UTC Time
Night	00:00–02:00
Early Morning	04:00–06:00
Morning	08:00–10:00
Midday	12:00–14:00
Afternoon	16:00–18:00
Evening	20:00–22:00

Table 2. Two-hour sessions used for the RTK evaluation.

Each session was initialised with a fresh filter state, ensuring no information carries over between sessions. Performance metrics include fix rate, time to first fix (TTFF), positioning precision (σ_E, σ_N, σ_U of Q=1 solutions), and wrong fix rate—defined as the percentage of Q=1 solutions with 3D deviation exceeding 50 mm from the reference position. Wrong fixes are not filtered but reported as a reliability metric, since a real-time rover user cannot distinguish correct from incorrect fixed solutions.

2.2.2 ZTD Estimation via PPP. The ZTD estimation capability of the Prali station was evaluated using the CSRS-PPP service with final precise satellite orbit and clock products, VMF1 mapping function, and integer ambiguity resolution. ZTD was decomposed into Zenith Hydrostatic Delay (ZHD), computed internally by CSRS-PPP, and Zenith Wet Delay (ZWD = ZTD − ZHD). The 12-hour observation period (00:00–12:00 UTC) provides a representative assessment of the station’s tropospheric monitoring capability under winter conditions.

3. Results and Discussion

3.1 RTK Positioning Performance

Table 3 summarises the RTK positioning results for the six two-hour sessions processed with SPIN3 VRS corrections. The results demonstrate that the LC station at Prali achieves centimetre-level positioning precision across a range of operational conditions, with best-case performance comparable to geodetic-grade receivers.

Session	Fix (%)	Rel. (%)	TTFF (min)	σ_{2D} (mm)	σ_U (mm)
Night	97.1	96.9	2.6	8.2	14.1
Early Morn.	85.8	75.7	16.5	14.4	44.6
Morning	57.2	54.2	4.5	14.4	21.7
Midday	49.5	35.7	21.5	23.0	24.0
Afternoon	89.7	79.8	8.7	11.2	15.3
Evening	3.1	2.3	105.7	17.7	27.8
Overall	63.7	57.4	—	15.5	34.9

Table 3. RTK positioning performance per session. Fix: Q=1; Rel.: reliable fix rate (Q=1 within 50 mm); TTFF: time to first fix; σ_{2D}: horizontal precision ($\sqrt{\sigma_E^2 + \sigma_N^2}$); σ_U: vertical precision.

Four out of six sessions achieved fix rates exceeding 57%, with the Night and Afternoon sessions reaching 97.1% and 89.7%, respectively. In these favourable sessions, the TTFF was below 9 minutes and the horizontal precision reached 8.2–11.2 mm (σ_{2D}), with vertical precision of 14.1–15.3 mm. The reliable fix rate—accounting for the exclusion of incorrectly resolved ambiguities—remained above 79% for both sessions, confirming that the LC u-blox ZED-F9P receiver delivers positioning performance fully compatible with rover-grade applications such as precision agriculture, and UAV navigation, even at 2200 m elevation in a challenging Alpine environment. The Morning and Early Morning sessions further confirmed centimetre-level precision when fixed ($\sigma_{2D} = 14.4$ mm), with the Morning session achieving a particularly rapid TTFF of 4.5 minutes. Across all sessions, the overall positioning precision for Q=1 solutions is $\sigma_{2D} = 15.5$ mm and $\sigma_U = 34.9$ mm.

The Midday and Evening sessions showed reduced performance, which is explained by well-understood environmental factors rather than hardware limitations. The Midday degradation (49.5% fix rate, 21.5 min TTFF) coincides with the daily peak of ionospheric activity, which is known to challenge ambiguity resolution for all dual-frequency receivers. The Evening session (3.1% fix rate) is primarily attributed to site-specific terrain obstructions, which severely limit the visible satellite constellation during this time window—a condition that would equally affect geodetic-grade equipment. Notably, even in these challenging sessions, the positioning precision of correctly resolved epochs remained at the centimetre level ($\sigma_{2D} \leq 24$ mm).

Figure 3 presents the ENU positioning offsets for all six sessions. The Night session converges rapidly and maintains centimetre-level stability throughout. The Afternoon session demonstrates sustained precision with a slight systematic offset in the Up component (∼−30 mm), attributed to residual tropospheric modelling differences at this altitude. The Morning and Midday sessions show intermittent fix–float transitions characteristic of active ionospheric periods, while the Evening session remains predominantly in float mode.

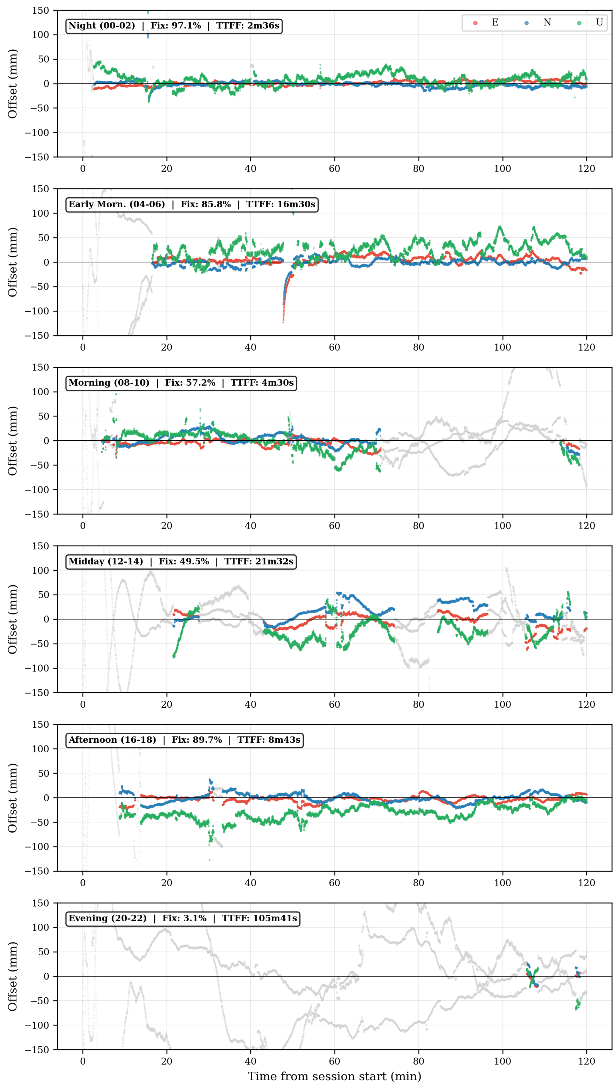

Figure 3. ENU positioning offsets for the six two-hour sessions. Coloured points: Q=1 (fixed) solutions (red: East, blue: North, green: Up); grey points: Q=2 (float) solutions. Each panel indicates the session time, fix rate, and TTFF.

Figure 4 confirms the centimetre-level horizontal precision, with the Night and Afternoon sessions showing compact clusters within the 10–20 mm radius. The Midday session presents a broader distribution consistent with the challenging ionospheric conditions, while the Early Morning scatter includes a transient linear feature corresponding to a sustained period of incorrect ambiguity resolution that persisted until changing satellite geometry allowed re-initialisation.

Among all Q=1 solutions, 9.9% were identified as wrong fixes based on their deviation from the reference coordinate, reducing the overall reliable fix rate to 57.4%. This distinction is critical for practical applications: unlike float solutions, which are clearly flagged by the receiver, wrong fixes are reported as fixed (Q=1) and are therefore indistinguishable from correct solutions in real time. The presence of wrong fixes is a known characteristic of the Fix-and-Hold ambiguity resolution strategy (Takasu and Yasuda, 2009, Bagheri et al., 2026), which prioritises fix availability over conservative validation. For operational deployments, this underscores the need for complementary quality control measures, such as tighter ratio test thresholds or position-domain consistency checks.

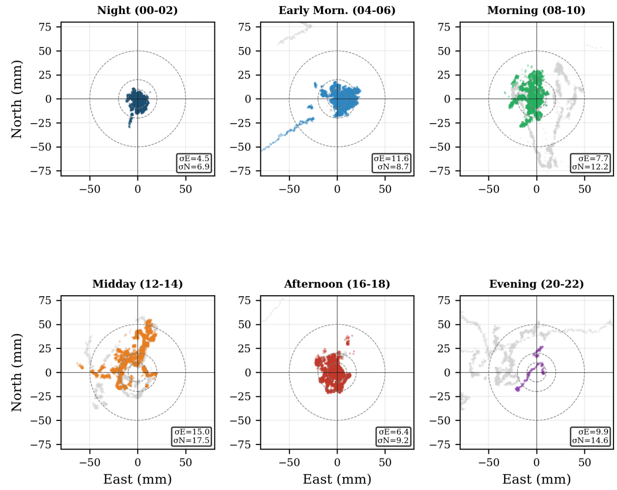

Figure 4. Horizontal position scatter (East vs. North) for Q=1 solutions per session. Dashed circles: 10, 20, and 50 mm radii. Grey points: float solutions. Insets show σ_E and σ_N per session.

3.2 ZTD Estimation

Figure 5 presents the ZTD time series derived from the Prali LC station using CSRS-PPP with 92% fixed ambiguities. The ZTD over the 12-hour observation period (00:00–12:00 UTC) shows a mean value of 1811.2 mm with a temporal standard deviation of 5.1 mm and a mean formal uncertainty of 15.8 mm per epoch.

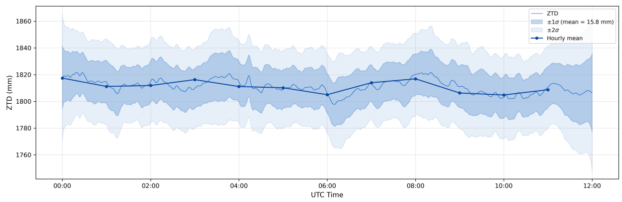

Figure 5. ZTD time series from the Prali LC station (CSRS-PPP, final products, 92% fixed ambiguities). Shaded bands indicate $\pm1\sigma$ and $\pm2\sigma$ formal uncertainty.

Figure 6 shows the decomposition into ZHD and ZWD. The ZHD, derived from VMF1 with gridded meteorological data, remains stable at 1770.4 ± 0.7 mm, reflecting the slowly varying surface pressure conditions. The ZWD, obtained as the difference between the estimated ZTD and the modelled ZHD, exhibits a general decreasing trend from approximately 46 mm at midnight to around 30 mm by midday, with superimposed short-term fluctuations of several millimetres (mean ZWD = 40.8 ± 4.9 mm). These values are consistent with dry winter tropospheric conditions at a high-altitude Alpine site, where the reduced column of atmosphere above the station results in lower absolute ZTD values compared to lowland stations, and the limited water vapour content produces correspondingly small ZWD.

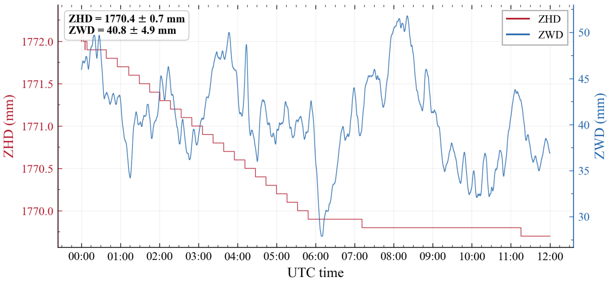

Figure 6. ZHD and ZWD from the Prali LC station.

These results demonstrate that the LC u-blox ZED-F9P receiver, despite the absence of antenna phase centre calibration, can produce physically consistent and temporally coherent tropospheric delay estimates when processed with precise products and integer ambiguity resolution. The ZTD temporal behaviour, including the diurnal ZHD decrease associated with surface pressure changes and the ZWD variability driven by water vapour fluctuations, is well resolved, confirming the potential of LC permanent stations for contributing to GNSS-based atmospheric monitoring at high-altitude sites.

4. Conclusions

This study evaluated the rover-side positioning performance and tropospheric delay estimation capability of a newly installed low-cost GNSS permanent station at Prali (2200 m elevation) in the Alpine region of Piedmont, Italy, within the framework of the PAIN AND GAIN project. The station, based on a u-blox ZED-F9P receiver with a broadband LC antenna and a Raspberry Pi computer, was assessed using VRS corrections from the SPIN3 professional CORS network.

The RTK evaluation, conducted across six independent two-hour sessions spanning a full diurnal cycle, demonstrated that the LC station achieves centimetre-level positioning precision under favourable conditions. The Night and Afternoon sessions reached fix rates of 97% and 90%, respectively, with horizontal precision of 8–11 mm and vertical precision of 14–15 mm—values fully consistent with published assessments of LC receivers in less demanding environments. The observed diurnal variability, with reduced performance during midday (ionospheric peak) and evening (terrain-limited satellite visibility), reflects well-understood environmental factors rather than hardware limitations, as the positioning precision of correctly resolved solutions remained at the centimetre level across all sessions. The identification of 9.9% wrong fixes among Q=1 solutions highlights a reliability aspect that is critical for operational deployments and is consistent with the known behaviour of the Fix-and-Hold ambiguity resolution strategy.

The ZTD estimation, performed using CSRS-PPP with final products and 92% integer ambiguity resolution, yielded physically consistent tropospheric delay values (mean ZTD = 1811 mm, ZWD = 41 mm) with well-resolved temporal variability, confirming that LC permanent stations can contribute meaningfully to GNSS-based atmospheric monitoring even at high-altitude sites.

These results confirm the viability of LC GNSS stations for centimetre-level positioning and atmospheric monitoring in demanding Alpine environments. Future work will focus on: (i) evaluating the station using network corrections generated by GNSMART 2; (ii) extending the ZTD assessment over longer periods with independent validation; (iii) investigating antenna phase centre calibration to improve absolute positioning accuracy; and (iv) deploying additional LC stations to progress toward a denser, cost-effective GNSS monitoring infrastructure in mountainous regions.

5. Acknowledgment

This study was carried out within the “PAIN AND GAIN — Positioning and INtelligent Alarms supported by a New Dense GNSS Affordable Infrastructure” project with the number 2022P8C7ZA — funded by European Union—Next Generation EU within the PRIN 2022 program (D.D. 104—02/02/2022 Ministero dell’Università e della Ricerca). This manuscript reflects only the authors’ views and opinions, and the Ministry cannot be considered responsible for them.

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