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RESEARCH

Low cost GNSS instruments for monitoring applications using Galileo

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Abstract
Low-cost multi-frequency GNSS receivers have recently become a viable alternative to geodetic-grade instrumentation for deformation and displacement monitoring applications. Among current GNSS constellations, Galileo offers specific advantages for such applications, including signal authentication through the Open Service Navigation Message Authentication (OSNMA), which enables navigation message authentication and increases the reliability of GNSS-based monitoring system. This study investigates the capability of low-cost GNSS instrumentation to detect millimetric displacements by using only Galileo observations. A dedicated experimental test network composed of five sites was established, where low-cost and geodetic-grade receivers operated simultaneously under identical conditions. At the central monitoring site, controlled three-dimensional displacements were imposed using a calibrated triaxial translation sledge. Three low-cost antennas with similar electronic electrical characteristics but different costs were tested in combination with a dual-frequency u-blox receiver. The collected datasets were processed on a daily basis using both Precise Point Positioning (PPP) and relative positioning approach, relying exclusively on Galileo E1 and E5a signals. The results demonstrate that low-cost GNSS systems can achieve coordinate repeatability comparable to geodetic-grade solutions, particularly for horizontal components. Millimetric horizontal displacements ($\geq$2.5 mm) are reliably detected in PPP, while relative positioning enables detection down to 1 mm for short baselines (100 m). Vertical displacement sensitivity is more dependent on antenna quality, highlighting the critical role of antenna design. Overall, the results confirm that low-cost Galileo-based GNSS systems represent a reliable and cost-effective solution for long-term displacement monitoring applications, provided that appropriate antenna choice and processing strategies are adopted.

Keywords Low-cost GNSS · Galileo · Displacement monitoring · Precise Point Positioning (PPP) · Relative positioning · GNSS antennas

Abstract (ITA)

I ricevitori GNSS multi-frequenza a basso costo sono recentemente diventati una valida alternativa alla strumentazione geodetica di alta gamma per applicazioni di monitoraggio delle deformazioni e degli spostamenti. Tra le attuali costellazioni GNSS, Galileo offre vantaggi specifici per questo tipo di applicazioni, tra cui l'autenticazione del segnale tramite il servizio Open Service Navigation Message Authentication (OSNMA), che aumenta la robustezza nei confronti di attacchi di spoofing e migliora l'affidabilità delle soluzioni di posizionamento in scenari di monitoraggio non presidiati. Il presente studio analizza la capacità della strumentazione GNSS a basso costo di rilevare spostamenti millimetrici utilizzando esclusivamente osservazioni della costellazione Galileo. È stata realizzata una rete sperimentale dedicata composta da cinque siti, nei quali ricevitori GNSS low-cost e di classe geodetica

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hanno operato simultaneamente in condizioni osservative identiche. Presso il sito centrale, che simula una stazione di monitoraggio, sono stati imposti spostamenti tridimensionali controllati mediante una slitta di traslazione triassiale calibrata. Sono state testate tre antenne GNSS a basso costo con caratteristiche elettroniche elettriche simili ma differenti livelli di costo, in combinazione con un ricevitore dual-frequency u-blox. I dataset acquisiti sono stati processati su base giornaliera utilizzando sia strategie di Precise Point Positioning (PPP) sia di posizionamento relativo, facendo esclusivamente uso dei segnali Galileo E1 ed E5. I risultati mostrano che i sistemi GNSS low-cost possono raggiungere una ripetibilità delle coordinate comparabile a quella delle soluzioni geodetiche di riferimento, in particolare per le componenti planimetriche. Spostamenti orizzontali millimetrici (≥ 2,5 mm) vengono rilevati in modo affidabile tramite PPP, mentre il posizionamento relativo consente di individuare spostamenti fino a 1 mm per baseline brevi (100 m). La sensibilità agli spostamenti verticali risulta maggiormente dipendente dalla qualità dell'antenna, evidenziando il ruolo cruciale del suo progetto. Nel complesso, i risultati confermano che i sistemi GNSS a basso costo basati su Galileo rappresentano una soluzione affidabile ed economicamente sostenibile per applicazioni di monitoraggio degli spostamenti a lungo termine, a condizione che vengano adottate scelte appropriate in termini di antenna e strategie di elaborazione.

Introduction

In recent years, low-cost multi-frequency GNSS (Global Navigation Satellite Systems) (Kazmierski et al. 2023) receivers have experienced significant technological improvements, making them increasingly attractive for geodetic monitoring applications that traditionally relied on high-end instrumentation (Hamza et al. 2023; Poluzzi et al. 2020; Radicioni et al. 2023). Among the available constellations, Galileo (Naciri et al. 2023) represents a particularly relevant case, as it is the first GNSS constellation to introduce a signal authentication service through the Open Service Navigation Message Authentication (OSNMA) (Hammarberg et al. 2024; Sarto et al. 2017). This feature enables navigation message authentication, allowing the verification of signal authenticity, which is a key requirement for monitoring applications operating in long-term monitoring systems operating without continuous on-site supervision or critical environments. In this context, the present study focuses exclusively on the Galileo constellation to assess the performance of low-cost GNSS equipment for displacement detection. To evaluate the performance of low-cost GNSS equipment and to define a repeatable methodology for testing receiver–antenna pairs, a dedicated experimental Test Network composed of five sites was established. Each site was equipped with both geodetic-grade and low-cost GNSS instrumentation operating simultaneously, enabling a direct comparison under identical observational conditions. At one site (DICAM01) simulating a monitoring station, the antennas were installed on a calibrated triaxial translation sledge, allowing the application of small, controlled displacements along the three axes. Three low-cost antennas with comparable electronic characteristics but different cost levels were tested. The acquired data were processed on a daily basis using open-source software, consistently with the requirements of low-cost monitoring applications. In addition, a quality control analysis of the RINEX data was performed to assess how much the estimated multipath and cycle slips values reflect on the accuracy of the solutions.

While previous studies have already demonstrated the potential of low-cost GNSS instrumentation for deformation monitoring, the scientific contribution of this work lies in the systematic assessment of a Galileo-only low-cost monitoring configuration under controlled millimetric displacements. In particular, the study combines: (i) a dedicated experimental test network with repeatable tridimensional imposed displacements, (ii) a comparative analysis of different low-cost antennas under identical conditions, and (iii) the exclusive use of Galileo E1 and E5a observations in both PPP and relative positioning strategies. The Galileo-only choice is not intended merely as a constellation-limitation experiment, but as a deliberate framework motivated by the specific advantages of Galileo for long-term unattended monitoring. In particular, the availability of the Open Service Navigation Message Authentication (OSNMA) introduces navigation message authentication, enabling the verification of signal authenticity, which is highly relevant for critical infrastructures and early warning applications where the reliability and trustworthiness of displacement alarms are essential. In this perspective, the manuscript aims to bridge the gap between low-cost GNSS monitoring performance and the emerging need for authenticated GNSS observations in security-sensitive monitoring scenarios.

Monitoring test site

The experimental network was established at the DICAM Department of the University of Bologna and was specifically designed as a controlled test field for GNSS-based monitoring applications. The network consists of four permanent reference stations distributed around a central site, named DICAM01, located at distances of approximately 100 m, 3 km, 6 km, and 14 km (Fig. 1).

This configuration allows the investigation of positioning performance as a function of baseline length, under well-defined and repeatable conditions. At the DICAM01 site, which simulates a monitored station, the GNSS antennas were installed on a triaxial north-facing sledge capable of imposing controlled displacements along the three local components with an accuracy of 0.1 mm. This setup enabled the imposition of known horizontal and vertical movements aligned. Each station was equipped with both geodetic-grade and low-cost GNSS receivers operating simultaneously, ensuring direct comparability of the observations. The geodetic installations included Leica and Trimble receivers coupled with AS11, AR10, and Zephyr3 antennas, while the low-cost hardware configuration is described in the following section.

Low-cost GNSS instrumentation

The low-cost GNSS instrumentation adopted in this study is based on the u-blox NEO-F9P receiver, a dual-frequency (L1/E1, L5/E5) and multi-constellation module. To investigate the impact of antenna characteristics on positioning performance, three low-cost GNSS antennas were selected, all featuring comparable electrical specifications but differing in geometry, internal filtering, and cost. The tested models are the Harxon GPS1000 (approximately \$740 in 2024), the Tallysman TW3972 (approximately \$420 in 2024), and the ArduSimple AS-ANT2B (approximately \$220 in 2024), whose costs are approximately one order of magnitude lower than geodetic-grade antennas (Fig. 2).

Each low-cost receiver was connected to a Raspberry Pi 5 mini-computer (8 GB RAM), which handled continuous data acquisition, system control, and automated transfer of raw observations to a central storage server. This architecture ensured fully automatic operation of the low-cost dataset throughout the experiment.

Experimentation and data processing

With the aim of determining the time required for the solutions to reach stability, the first antenna (Harxon) was operated over an extended acquisition period of 108 days, while the second (Tallysman) and the third (ArduSimple) were observed for 49 days and 44 days, respectively. During each experimental session, an identical displacement pattern was applied, consisting of two horizontal shifts of 5 mm and

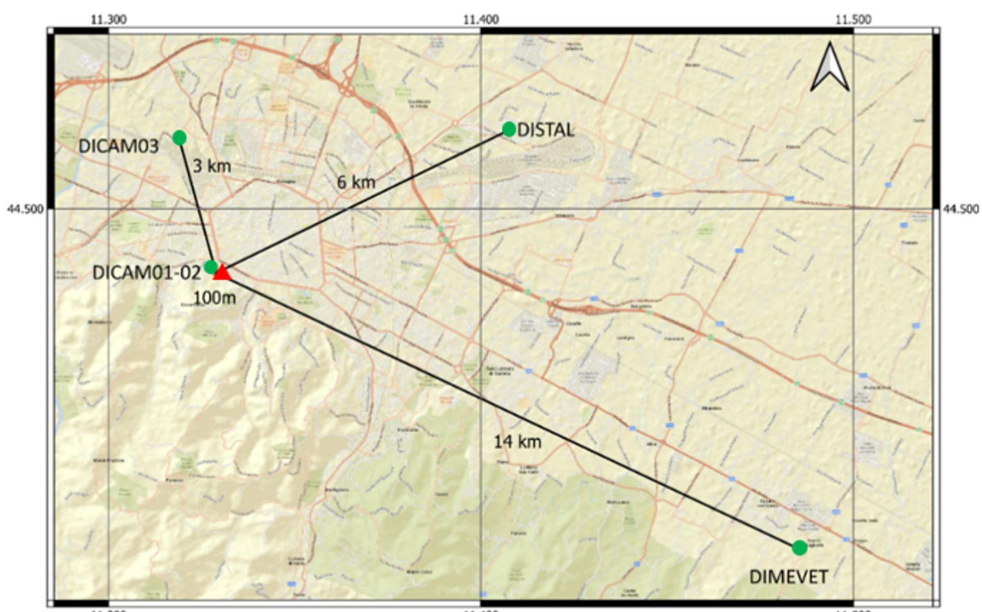

Fig. 1 Map of the Test Network, Bologna (ITA). The red triangle represents the monitored site (DICAM01), and the green dots represent the four reference stations located at increasing distances

Fig. 2 Low-cost antennas used in the experimentation

2.5 mm, and two vertical movements of 10 mm and 5 mm. Additionally, for the Harxon GPS1000 antenna, additional smaller displacements of 1 mm in the two planimetric components and 2.5 mm in height were imposed in order to investigate the minimum detectable displacement threshold.

The collected datasets were processed using both Precise Point Positioning (PPP)(Kouba et al. 2017; Kouba and Héroux 2001) and relative positioning strategies (Poluzzi et al. 2021), adopting MGEX(Dach et al. 2024) precise products and Vienna Mapping Functions (VMF1)(Kouba 2008) for tropospheric modelling in both approaches, and considering exclusively observations from the Galileo constellation. This choice was motivated by the specific relevance of Galileo for long-term monitoring applications, where the availability of OSNMA enables navigation message authentication, an important feature for the reliability of displacement alarms in early warning systems. In addition, the adoption of 24-hour static sessions minimizes the precision gap with respect to multi-constellation processing. PPP was carried out using the PRIDE PPP-AR software (Cappuccio et al. 2026; Geng et al. 2019), which provides daily position estimates in the ITRF2020 reference frame (Altamimi et al. 2023). To isolate the local displacements induced by the translation sledge, the average tectonic motion of the Eurasian plate was removed from the resulting coordinate time series, allowing a direct comparison with relative positioning.

Differential processing was performed using the open-source RTKLIB Demo5 software (Takasu 2009), specifically optimized for low-cost GNSS receivers (https://github.com/rinex20/RTKLIB-demo5). The differential approach inherently reduces common spatial-related errors between stations and so greatly improves the accuracy when the distance is short. The position time series of the monitored DICAM01 site was computed from the other four baselines.

The main precise products, geophysical models, and processing parameters adopted in the workflow are summarized in Table 1, in order to ensure full methodological reproducibility.

Table 1 Main precise products, geophysical models, and processing parameters adopted for the Galileo-only GNSS processing

Product	Source	File
Orbits	http://ftp.aiub.unibe.ch/CODE_MGEX/CODE/2023/	COD0MGXFIN*05 M*.SP3
Clock		COD0MGXFIN*30S*.CLK
Bias		COD0MGXPSFIN*.BIA
Sat. Attitude		COD0MGXFIN*30S*.OBX
Rec. antenna calibration	https://files.igs.org/pub/station/general/	Igs20.atx
Sat. antenna calibration		
Phase center mass correction		
	Model	
EOP, Solid and Pole Tides	IERS 2010 conventions (Technical note 36), Chap. 7	
Ocean-Load model	FES2014b	
Tropospheric mapping function	VMF-1	
Parameter	***Value***	
Elevation mask	10°	
Carrier signal	E1-E5a	

In both the PPP and the differenced processing, only Galileo E1 and E5a observations were used. Prior to computing the statistics, the discontinuities introduced by the imposed displacements were removed from the time series to isolate the intrinsic scatter of the solutions. Figure 3 shows the histograms of the standard deviations of the daily coordinates for the three geodetic components (North, East, Up).

The dispersion of the North and East coordinates is consistently lower than that of the vertical component, with the latter exhibiting standard deviations approximately two to three times larger. Excluding the results obtained with the Tallysman TW3972 antenna at the DISTAL site, the standard deviations of the horizontal components range between 0.9 mm and 2.0 mm, with an average value of 1.4 mm.

Results

This section presents the results of the experimental analysis based on Galileo code and carrier-phase observations. The outcomes are discussed by processing strategy, considering first the PPP solutions and then the relative positioning results. For both approaches, coordinate repeatability is evaluated as an indicator of the sensitivity to displacement detection. Selected time series from the monitoring site equipped with the translation sledge are also shown, together with Quality Control of the acquired RINEX data.

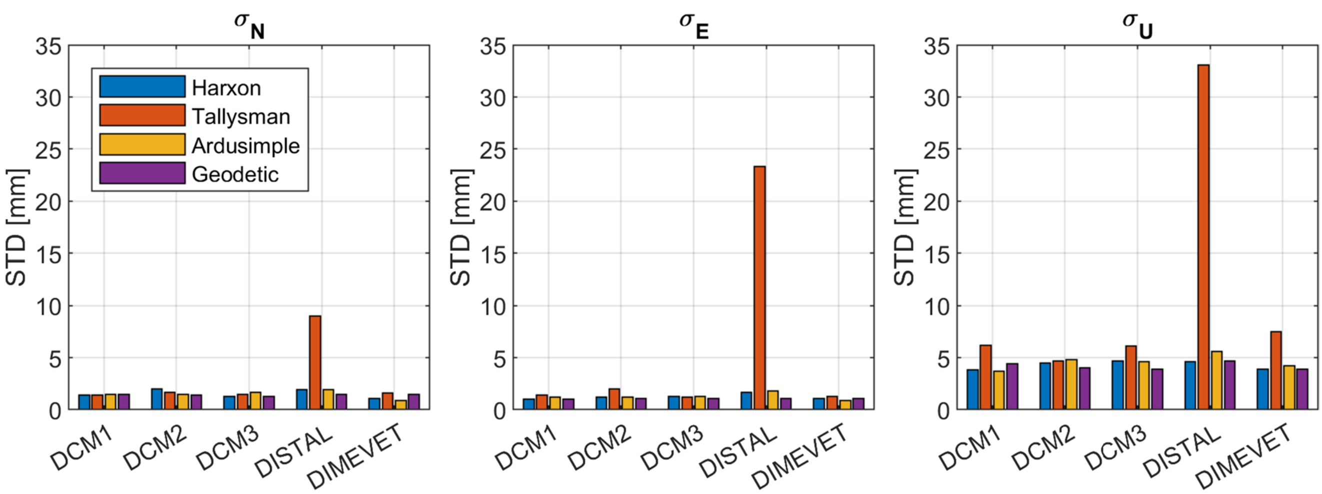

Fig. 3 Histogram of the Standard Deviation of the three components (NEU) for each site and for each antenna

For the vertical component, the corresponding values are 3.7 mm, 7.5 mm, and 4.7 mm.

Overall, the coordinate repeatability achieved using low-cost hardware is comparable to that obtained with geodetic-grade instrumentation. This is particularly evident for the Harxon GPS1000 and the ArduSimple AS-ANT2B antennas, whose performance closely matches that of high-end systems. The Tallysman antenna exhibits slightly poorer performance, especially in the vertical component. This behavior is most pronounced at the DISTAL site, where the antenna installation is affected by nearby flat metallic surfaces, which enhance multipath effects. The fact that similar issues are not observed for the other low-cost antennas suggests that the Tallysman antenna can be considered less performant in critical environments.

The ability of the Galileo-based PPP solutions to detect known displacements was evaluated using the data collected at the DICAM01 site, where controlled movements were imposed through the triaxial translation sledge. Figure 4 shows an example of the resulting coordinate time series, comparing the geodetic-grade station to the low-cost configuration using the Tallysman antenna.

The time series clearly demonstrate that horizontal displacements are detected with similar effectiveness by both the geodetic and low-cost systems. Even when using the antenna that showed the weakest performance in terms of repeatability, the low-cost station is capable of identifying horizontal shifts of 2.5 mm, provided that a sufficient number of daily solutions is available.

In contrast, the sensitivity to vertical displacements using Tallysman antenna is lower. While a 5 mm vertical movement is clearly detectable in the geodetic-grade time series, the same displacement is not reliably observable when using the low-cost station. However, when considering the Harxon and ArduSimple antennas, the vertical component shows a much closer agreement with the geodetic reference, indicating that antenna choice plays a crucial role in vertical displacement detection when processing is limited to Galileo-based observations.

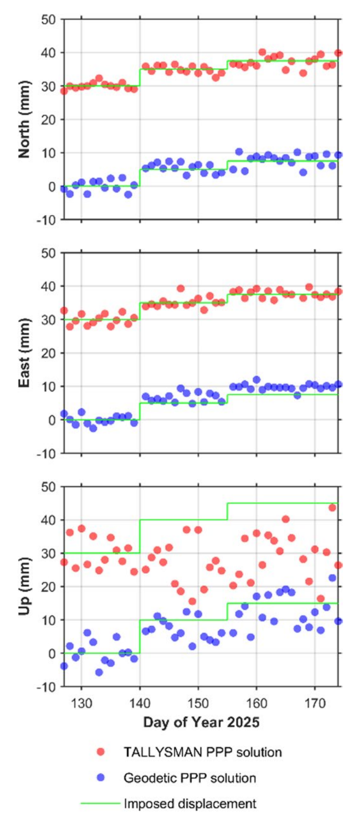

Fig. 4 Plot of the time series computed at the DICAM01 site, where calibrated displacements were imposed. Blue dots refer to the geodetic-class GNSS station and red dots represent coordinates from the low-cost hardware, considering the Tallysman antenna, namely the one with the poorer performances in the test

The results obtained from differential processing were analyzed by computing the relative coordinates of the DICAM01 site with respect to the surrounding reference stations at increasing baseline lengths. Figure 5 presents the histograms of the standard deviations of the relative coordinates as a function of baseline length and antenna type.

For the shortest baseline (100 m), the repeatability of the solutions is remarkably high, with standard deviations consistently below 1 mm for Harxon, ArduSimple, and the geodetic-grade instrumentation, confirming the effectiveness of the differential approach at short distances. For short baselines, the weakness of the Tallysman antenna compared to others is enhanced.

As the baseline length increases, a progressive degradation of coordinate repeatability is observed. This effect is more pronounced for the vertical component, which exhibits larger scatter compared to the horizontal components. Nevertheless, even for the longest baseline (14 km), the differences between high-end and low-cost instrumentation remain limited. Once again, the Tallysman antenna shows a slightly reduced performance, especially in the DISTAL (6 km) site, although the degradation is less severe than in the PPP case.

It is worth noting that, despite the presence of significant multipath effects at the DISTAL site, the impact on the differential solutions remains limited. This suggests that the double-difference strategy, even when restricted to a single constellation, effectively mitigates site-specific error sources affecting PPP.

Figure 6 illustrates the coordinate time series obtained at the DICAM01 site using the Harxon GPS1000 antenna, comparing results from the shortest (100 m) and longest (14 km) baselines. Darker symbols correspond to the short baseline, while lighter colors indicate the longer one

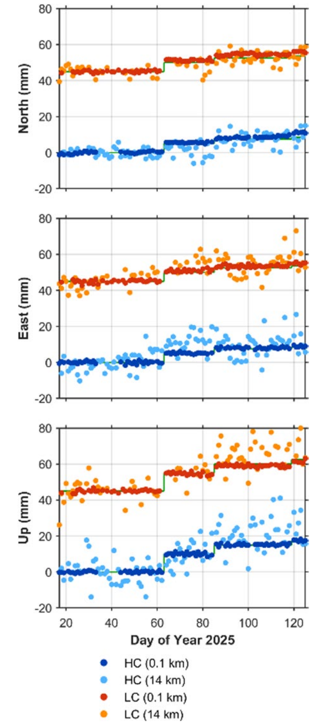

Fig. 6 Plot of the time series computed at the DICAM01 site, where calibrated displacements were imposed. Blue dots refer to the geodetic-class GNSS station (HC) and red dots represent coordinates from the low-cost hardware (LC) considering the Harxon antenna, both for 100 m baselines. Light blue and orange dots refer to 14 Km baselines

For the 100 m baseline, the time series clearly show that even the smallest imposed displacements of 1 mm in the horizontal components (especially in East) and 2.5 mm in height are detectable. For the 14 km baseline, the detection capability is reduced. In this case, only the larger displacements (5 mm horizontally and 10 mm vertically) can be reliably identified in the time series. Nevertheless, no significant differences are observed between the geodetic and low-cost solutions, confirming that baseline length, rather than receiver class, is the dominant factor affecting performance in this configuration.

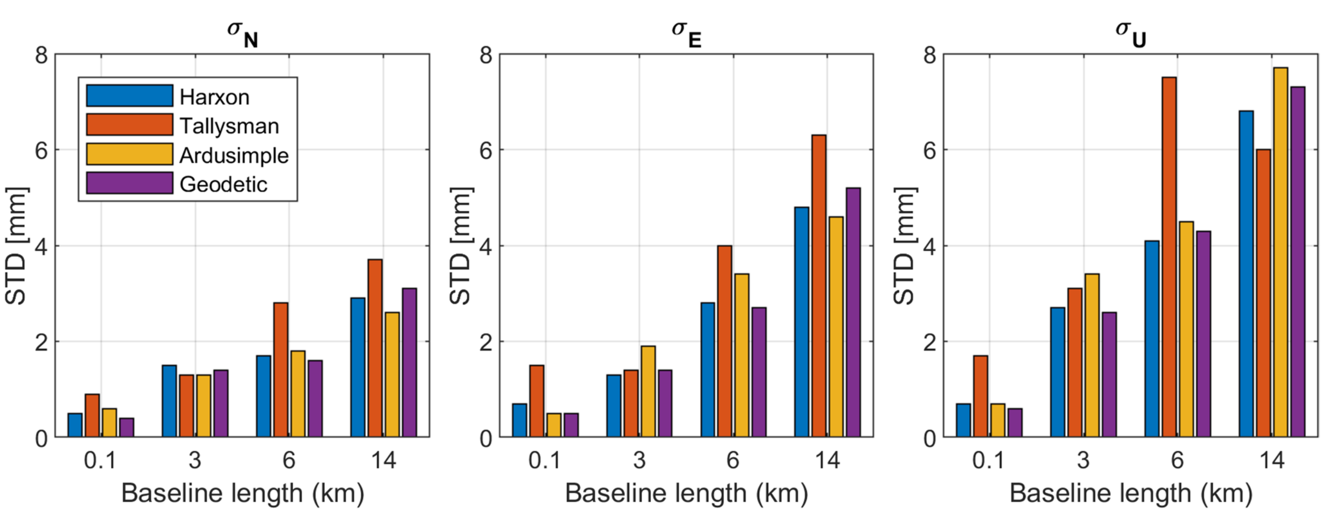

Fig. 5 Histogram of standard deviations of the coordinates computed over the DICAM01 test site depending on the distance to the reference station and the used antenna

Finally, a quality control analysis of the acquired RINEX files was carried out using the RINGO software (Kawamoto et al. 2023). Figure 7 shows the multipath estimates on the Galileo E1 and E5a signals, together with the percentage of cycle slips relative to the total number of daily observations, computed over the entire observation period. Different colors represent the five sites of the experimental network, while the antenna type varies according to the testing period.

The analysis reveals marked differences in the response of the tested antennas to changing environmental conditions. The Tallysman antenna is the most affected by multipath, despite being equipped with a dedicated ground plane. This effect is particularly evident on the E5a signal at the DISTAL site and explains the degradation observed in the PPP results for this configuration. The Harxon antenna also exhibits increased multipath on the E1 frequency at the DICAM03 site, whereas the E5a signal appears more stable. In this case, the low multipath level on E5a likely compensates for the higher noise on E1, resulting in negligible effects on the coordinate solutions. Overall, the geodetic class antennas show lower multipath while working in good environmental conditions. At the DISTAL site, where a metallic surface close to the antennas causes multipath, also the Zephyr3 Trimble antenna exhibits strong multipath, even more than low-cost antennas on the L5.

Regarding cycle slips, the Harxon antenna shows the highest sensitivity to local conditions, with pronounced peaks occurring at the DISTAL site. These events are generally confined to short time intervals and do not significantly affect daily position estimates. However, they could represent a limitation for kinematic or high-rate applications. Among the tested models, the ArduSimple antenna provides the best overall performance in terms of cycle slip reduction, comparable to geodetic class antennas.

Discussion

The controlled experimental setup enabled a direct comparison between geodetic-grade and low-cost receiver–antenna configurations under identical environmental and observational conditions, allowing a robust interpretation of the factors controlling the final positioning performance. The results demonstrate that, for both PPP and differential processing strategies, low-cost GNSS hardware can achieve millimetric coordinate repeatability comparable to that of high-end systems when daily static sessions are adopted. A key outcome of the analysis is that the dominant factor affecting the final precision is not the receiver class itself, but rather the antenna characteristics and the local installation environment. This is particularly evident in the vertical component, where residual multipath and antenna sensitivity produce a stronger degradation than in the horizontal directions.

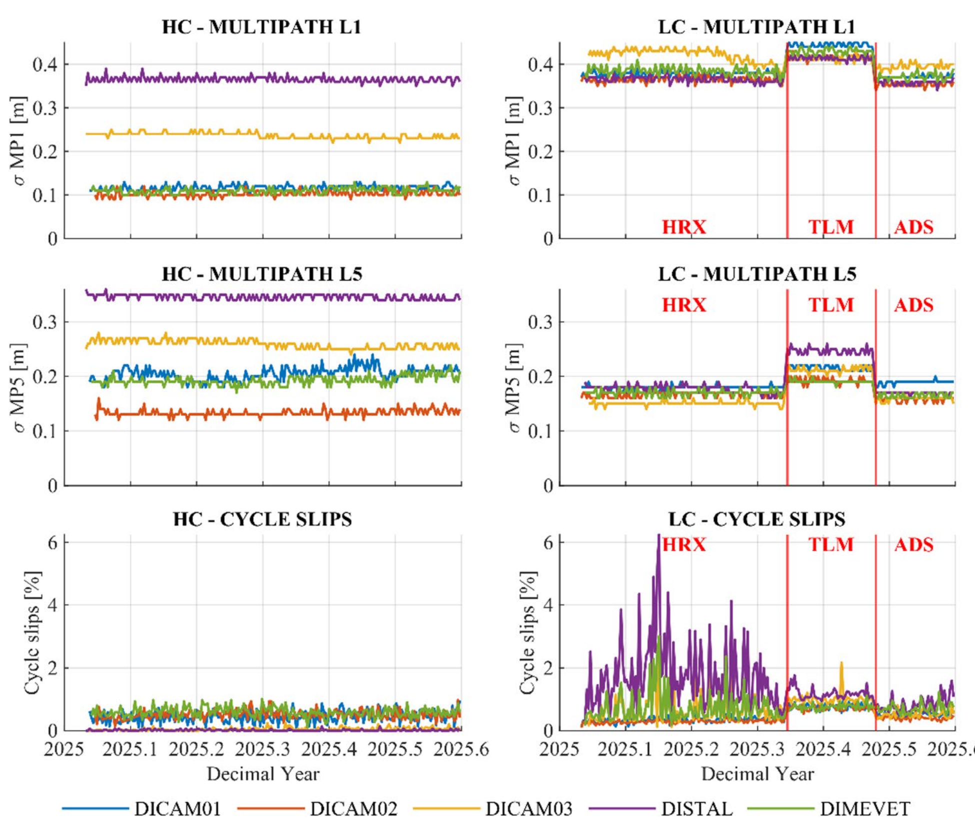

Fig. 7 Quality Control analysis of the data acquired over the entire test period for the low-cost and high-end hardware. Different low-cost antennas were mounted on different time spans. Colors relate to the five different test-sites. Upper plots show multipath over Galileo E1 and Galileo E5a, while the bottom plot reports the percentage of daily cycle-slips over the total daily observations

The comparative analysis of the three tested antennas highlights that low-cost solutions with similar nominal electrical characteristics may exhibit significantly different behavior under real monitoring conditions. In particular, the results obtained at the DISTAL site confirm that nearby reflective surfaces can strongly amplify antenna-dependent multipath effects, especially in PPP solutions. This finding has important practical implications, as it suggests that in long-term monitoring applications the installation strategy and antenna design are often more critical than the nominal cost of the receiver.

The differential processing results further confirm the strong effectiveness of short baselines in displacement monitoring. For the 100 m baseline, the capability to detect horizontal displacements down to 1 mm demonstrates that the double-difference approach efficiently mitigates local residual errors even when only Galileo observations are considered. As the baseline length increases, the progressive degradation mainly reflects the reduced spatial correlation of atmospheric and orbital residuals rather than limitations of the low-cost hardware. From an application perspective, the use of Galileo-only daily solutions proved particularly meaningful. For 24-hour static sessions, the precision gap with respect to multi-constellation processing is expected to remain marginal, while Galileo offers the additional advantage of OSNMA-based navigation message authentication. This aspect is especially relevant for long-term monitoring and early warning systems, where the reliability of displacement alarms is as important as the positioning precision itself.

Conclusions

This study confirms that low-cost Galileo-based GNSS systems can provide a robust and cost-effective sustainable solution for long-term static displacement monitoring, provided that appropriate antenna selection, installation conditions, and processing strategies are adopted. The results highlight that antenna behavior and environmental conditions play a more critical role than receiver class, especially for the vertical component, while short baselines enable reliable detection of sub-millimetric horizontal displacements. Overall, the Galileo-only approach proved fully suitable for 24-hour static monitoring sessions, combining millimetric repeatability with the added value of navigation message authentication. Future work will focus on extending the analysis to multi-constellation configurations and investigating the performance of low-cost hardware in near-real-time and kinematic monitoring scenarios.

Author contributions All authors contributed to the study conception and design. Del Ciondolo G. reorganized the data and performed the PRIDE PPP-AR and rtk-lib processing. Cappuccio M. supervised the PPP processing, provided guidelines for the post-processing strategy and analyzed the results. Luca P., Tavasci L. and Gandolfi S. supervised both the computations and the paper writing. The first draft of the manuscript was written by Cappuccio M. All authors read, commented and approved the final manuscript.

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Data availability The data on which this research is based are available from the corresponding author exclusively for fully justified scientific purposes.

Declarations

Competing interests The authors declare no competing interests.

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