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Assessing the Feasibility and Performance of Low-Cost GNSS Receivers for Precise Point Positioning Across Diverse Environments

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ABSTRACT

The recent evolution of low-cost dual-frequency Global Navigation Satellite System (GNSS) receivers has created new opportunities for high-precision positioning in cost-sensitive applications. However, limited studies have systematically evaluated their Precise Point Positioning (PPP) performance under varying environmental conditions and processing configurations. This study assesses the feasibility and positioning performance of a low-cost dual-frequency GNSS receiver in semi-obstructed and open-sky environments using PPP and Standard Point Positioning (SPP) techniques.

Static GNSS observations were collected with and without a manufacturer-provided ground plane to evaluate its effectiveness in mitigating multipath effects. PPP solutions were processed using ultra-rapid, rapid, and final International GNSS Service (IGS) orbit and clock products, and performance was compared across different environmental conditions.

Results indicate that environmental condition is the dominant factor influencing positioning performance. The use of a ground plane reduced multipath errors, particularly in obstructed environments. In open-sky conditions, PPP achieved centimeter to sub-decimetre level accuracy, especially when using rapid or final IGS products, whereas SPP remained limited to meter-level accuracy. Final products provided the highest positioning precision, while rapid products offered a practical balance between accuracy and convergence time.

The results demonstrate that low-cost GNSS receivers can support reliable high-precision positioning in professional and mass-market applications when supported by appropriate processing strategies and hardware configurations.

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1. Introduction

Global Navigation Satellite Systems (GNSS) have become integral to a wide range of geoscientific applications and have significantly transformed land surveying by enabling the determination of position coordinates with centimeter-level accuracy in real time and sub-centimeter accuracy through post-processing techniques (Wielgocka et al., 2021). Under open-sky conditions, more than 20 satellites are typically visible above the horizon, allowing users to access signals from the four primary GNSS constellations, transmitted across multiple frequency bands. This extensive satellite and frequency availability facilitates real-time positioning with centimeter-level precision for general users (Robustelli et al., 2023).

Two primary approaches are employed to obtain high-precision position coordinates: absolute positioning and relative positioning. In absolute positioning, satellite ephemerides and coordinates serve as the reference frame, whereas relative positioning relies on a reference station with known coordinates. Thus, the accuracy of a GNSS-derived position is directly dependent on the precision of the satellite orbit data or the reference station coordinates (Wielgocka et al., 2021).

Among absolute positioning techniques, Precise Point Positioning (PPP), introduced by Zumberge et al. (1997), has emerged as a widely adopted method due to its ability to incorporate precise satellite orbit and clock corrections, along with various bias products, to achieve high positional accuracy (Wielgocka et al., 2021). PPP is increasingly applied not only in surveying but also in diverse geoscientific domains, including atmospheric research, tectonic and geophysical monitoring, and early warning systems for natural hazards such as earthquakes and tsunamis. Unlike relative positioning methods, the performance of PPP is primarily governed by the quality of the satellite orbit and clock products. As a result, recent research has focused on improving these products, refining GNSS algorithms, and advancing GNSS modernization efforts (Gill et al., 2018; Ogutcu & Farhan, 2022).

In recent years, precise satellite orbit and clock products provided by the International GNSS Service (IGS) and the Multi-GNSS Experiment (MGEX) have been increasingly utilized in PPP applications. Currently, five types of GNSS orbit and clock products are available: broadcast ephemeris and ultra-rapid (predicted-half) products for real-time use, and ultra-rapid (observed-half), rapid, and final products for post-processing. Among these, broadcast ephemeris and ultra-rapid (predicted-half) products are generally unsuitable for high-precision PPP due to their limited accuracy. Moreover, due to the need for rapid availability, Analysis Centers (ACs) typically employ fewer reference stations when generating ultra-rapid and rapid products, in contrast to the more comprehensive data processing used to produce final products (Ogutcu & Farhan, 2022).

Numerous studies have examined the influence of different IGS orbit and clock product types, namely ultra-rapid, rapid, and final, on PPP positioning accuracy. Fumin and Jin (2011) assessed the performance of PPP using IGS broadcast, ultra-rapid, and rapid products, concluding that while broadcast ephemerides achieve only sub-meter-level accuracy, rapid and ultra-rapid products enable positioning at the centimeter level. Similarly, Park and Jung (2014) evaluated the impact of ultra-rapid (observed-half), rapid, and final products, reporting that the standard deviation associated with ultra-rapid products reached up to 3.9 cm, whereas rapid and final products maintained standard deviations below 1 cm. In a broader analysis, Ogutcu and Farhan (2022) investigated PPP performance across multiple constellations (GPS, GLONASS, Galileo, and BeiDou) using ultra-rapid and rapid products provided by seven different analysis centers. Their findings indicated that GFZ/NRCan and CODE/NRCan offered the highest PPP accuracy for GPS-only solutions, while GFZ also yielded superior performance for Galileo- and BeiDou-only processing. These results highlight the variability in PPP performance depending on the satellite constellation, product type, and analysis center, underscoring the importance of selecting appropriate processing resources.

PPP has established itself as a reliable and efficient technique, capable of delivering centimeter- to millimeter-level positioning accuracy using a single GNSS receiver. Unlike relative positioning methods, which require concurrent observations from at least two stations, PPP operates using un-differenced carrier-phase and pseudo-range measurements (Kouba & Héroux, 2001; Zumberge et al., 1997). For many years, achieving such high accuracy was limited to the use of dual-frequency, geodetic-grade receivers. While these receivers offer highly accurate code and phase measurements, their high cost has constrained their adoption in many practical applications (Biagi et al., 2016; Cina & Piras, 2015; Wielgocka et al., 2021). With the continuous evolution of GNSS-based technologies and the expanding range of positioning applications, there has been growing demand from both professional and consumer markets for cost-effective high-accuracy solutions (Gill et al., 2018). In response, recent advances in GNSS receiver design have led to the emergence of low-cost devices that significantly reduce the financial barrier to entry. These receivers now provide a viable alternative to geodetic-grade equipment, expanding access to precise positioning for a broader range of users and application domains (Robustelli et al., 2023).

Low-cost single-frequency GNSS receivers have demonstrated adequate precision for a variety of applications in geodetic surveying, geophysical monitoring, and navigation, particularly when used with relative positioning techniques such as Real-Time Kinematic (RTK). However, one of the major limitations of single-frequency systems is their susceptibility to ionospheric delay, which significantly affects the accuracy of both PPP (Gill et al., 2018) and long-baseline RTK solutions (Cina & Piras, 2015). Furthermore, the performance of these receivers often worsens in urban environments due to the presence of multipath effects, preventing them from achieving their nominal specifications (Jackson et al., 2018). The emergence of low-cost dual-frequency GNSS receivers has mitigated several of these limitations. By utilizing dual-frequency measurements, ionospheric delay can be effectively eliminated through linear combination techniques, resulting in improved accuracy and reliability (Wielgocka et al., 2021). One of the most notable advancements in this category is the u-blox ZED-F9P chipset, developed by the Swiss manufacturer u-blox. This dual-frequency, multi-constellation receiver, typically priced below USD 200, has become one of the most widely used low-cost GNSS modules on the market (Hohensinn et al., 2022).

In recent years, multiple studies have evaluated the performance of such low-cost GNSS modules. For example, Hamza, Stopar and Sterle (2021) assessed the u-blox ZED-F9P receiver paired with various uncalibrated low-cost helix antennas and compared the results against those from calibrated geodetic-grade antennas. Their findings demonstrated that low-cost configurations could achieve millimeter-level precision in some conditions. They concluded that, although geodetic-grade equipment continues to offer superior performance, the significantly lower cost of low-cost systems makes them a compelling alternative for many geodetic applications. In a subsequent study, Hamza, Stopar, Ambrožič, et al. (2021) further demonstrated that centimeter-level positioning accuracy is achievable using PPP in post-processing mode with low-cost antennas and receivers. Wielgocka et al. (2021) conducted a series of field experiments to evaluate the performance of the u-blox ZED-F9P receiver in combination with the u-blox ANN-MB-00-00 antenna. In static mode, ambiguity resolution was successfully achieved in approximately 80% of cases, with horizontal positioning accuracy reaching within a few centimeters after one hour of observation. PPP processing yielded similar accuracy but required an observation period of up to 2.5 hours. For RTK and Network RTK (NRTK) configurations, horizontal accuracy better than 5 cm and vertical accuracy below 10 cm were consistently observed. Gill et al. (2018) compared geodetic-grade, low-cost, and smartphone-based receivers, showing that low-cost systems can achieve sub-meter to decimetre-level PPP accuracy, albeit with longer convergence times.

Despite these advances, limited research has systematically evaluated the combined effects of environmental obstruction, ground-plane usage, and different IGS orbit and clock products on PPP performance using a single low-cost dual-frequency GNSS receiver. In particular, comparative analyses between semi-obstructed and open-sky environments remain limited for practical low-cost receiver–antenna configurations.

Multipath effects remain one of the major sources of positioning error for low-cost GNSS receivers, especially in partially obstructed urban environments. Ground planes are commonly employed to reduce reflected signal interference by attenuating low-elevation multipath signals; however, their effectiveness for low-cost dual-frequency PPP applications under varying environmental conditions has not yet been fully quantified.

Therefore, this study aims to:

1. Evaluate the PPP performance of the low-cost u-blox ZED-F9P GNSS receiver under different environmental conditions;
2. Assess the influence of a metallic ground plane on multipath mitigation and positioning quality;
3. Compare PPP solutions generated using ultra-rapid, rapid, and final IGS orbit and clock products; and
4. Compare PPP and Standard Point Positioning (SPP) performance against reference coordinates obtained from geodetic-grade observations.

Unlike previous studies that primarily focused on open-sky PPP performance or RTK applications, this study systematically evaluates the combined influence of environmental obstruction, ground-plane usage, and multiple IGS precise product types within a unified low-cost PPP framework. The findings contribute to understanding the operational capabilities and limitations of low-cost dual-frequency GNSS systems for precise positioning applications in both favourable and partially obstructed environments in Tehran area.

2. Materials and Methods

2.1 Low-Cost Receiver and Antenna

The low-cost GNSS hardware used in this study is the u-blox ZED-F9P module, which supports 184 channels and is capable of receiving dual-frequency signals (F1 and F2) from all major global satellite navigation constellations. Specifically, it tracks the GPS C/A code on the L1 band and the modernized L2C signal on the L2 band; GLONASS open access L1OF and L2OF signals on L1 and L2 bands; Galileo E1B/E1C signals on the E1 band and E5b on the E5 band; and BeiDou B1I and B2I signals (https://www.u-blox.com/en/product/zed-f9p-module).

The receiver was paired with the standard u-blox ANN-MB-00-00 patch antenna, which is a right-hand circularly polarized (RHCP), dual-band antenna designed for reception of L1 and L2/E5b/B2I signals. According to manufacturer specifications, typical Phase Center Offset (PCO) and Phase Center Variation (PCV) values are only provided for GPS L1 and L2 frequencies. The PCO is reported to be less than 5 mm in the horizontal plane, and less than 8.9 mm (L1) and 7.6 mm (L2) in the vertical direction. PCV values are under 5 mm and 10 mm for L1 and L2, respectively, across all azimuth and elevation angles(https://www.u-blox.com/en/product/ann-mb-series).

2.2. Reference Data

To accurately assess the positioning performance of the low-cost receiver, it is essential to establish high-precision reference coordinates for each observation station. For this purpose, a geodetic-grade Hi-Target V90Plus GNSS receiver was employed to perform static measurements at each site. Data were collected over a 3-hour continuous session per station, allowing for sufficient observation time to ensure precision.

The final reference coordinates were computed using the PPP method, incorporating Final orbit and clock products provided by the IGS. These final products offer the highest level of precision available for PPP method, ensuring that the reference positions are accurate and reliable. To enable consistent spatial analysis and facilitate accurate comparisons among the observation stations, the computed geodetic coordinates were projected into the Universal Transverse Mercator (UTM) coordinate system, Zone 39N, based on the WGS84 datum, which corresponds to the geographic location of the study area in Tehran. This projection ensures that all positional data are represented in metric units (meters), making them suitable for mapping, spatial visualization, and quantitative analysis.

2.3. Precise Point Positioning Mathematical Model

PPP enables high-accuracy single-receiver GNSS positioning by utilizing external, high-precision satellite orbit and clock correction products. To achieve accurate positioning, PPP also incorporates several auxiliary models and corrections, including those for satellite antenna phase center variations, phase wind-up effects, and solid Earth tides (Grinter & Janssen, 2012). Traditional PPP implementations often rely on a float ambiguity solution, which requires a long convergence time to achieve centimeter-level accuracy.

A key component of the PPP approach is the use of ionosphere-free (IF) linear combinations of dual-frequency GNSS observations. These combinations effectively eliminate the first-order ionospheric delay, which is one of the major sources of GNSS error. The general observation equations for the ionosphere-free pseudorange and carrier phase measurements can be expressed as (Leick et al., 2015; Ogutcu & Farhan, 2022):

$$P_{IF,r}^{s,j} = \rho + c * \left(dt_r - dt^{s,j}\right) + d_{trop} + HD_{P,r,IF} - HD_{P,IF}^{s,j} + \varepsilon_{P,IF}^{s,j} \quad (1)$$

$$\phi_{IF,r}^{s,j} = \rho + c * \left(dt_r - dt^{s,j}\right) + d_{trop} + \lambda_{IF}^{s,j} * N_{r,IF}^{s,j} + HD_{\phi,r,IF} - HD_{\phi,IF}^{\{sj\}} + \varepsilon_{\phi,IF}^{s,j} \quad (2)$$

where s and j denote the satellite and GNSS system indices, respectively. r is receiver index. ρ is geometric range between satellite and receiver (in meters). c is speed of light (in m/s). dtr and $dt^{s,j}$ are receiver and satellite clock offset (in seconds) respectively. d_{trop} is the tropospheric delay (in meters). $\lambda_{IF}^{s,j}$ is wavelength of the ionosphere-free combination. $N_{r,IF}^{s,j}$ is carrier phase ambiguity (float value). HD is Hardware delays for code and phase measurements and ε is the measurement noise.

To remove satellite orbit and clock errors, precise products from an Analysis Center (AC), such as those provided by the IGS, are applied (Kouba & Héroux, 2001). Satellite hardware delays in pseudorange measurements are generally absorbed into the satellite clock corrections. Similarly, the receiver's code hardware delay is absorbed into the receiver clock bias estimate. Uncalibrated phase delays from both the satellite and receiver are combined with the carrier-phase ambiguity term, preventing direct resolution of integer ambiguities in traditional float PPP (Ogutcu & Farhan, 2022; Xiao et al., 2018).

The ionosphere-free pseudorange and phase observables can be expressed using dual-frequency observations as follows:

$$P_{IF,r}^{s,j} = \frac{\left(f_1^2 * P_{1,r}^{s,j} - f_2^2 * P_{2,r}^{s,j}\right)}{\left(f_1^2 - f_2^2\right)} \quad (3)$$

$$\phi_{IF,r}^{s,j} = \frac{f_1^2 * \phi_{1,r}^{s,j} - f_2^2 * \phi_{2,r}^{s,j}}{f_1^2 - f_2^2} \quad (4)$$

Here, f_1 and f_2 are the carrier frequencies, while P_1, P_2 and ϕ_1 , ϕ_2 denote the pseudo range and carrier-phase measurements on the two respective frequencies. The effective wavelength of the ionosphere-free combination and its corresponding ambiguity are defined as:

$$\lambda_{IF}^{s,j} = \frac{f_1^2}{f_1^2 - f_2^2} * \lambda_1 - \frac{f_2^2}{f_1^2 - f_2^2} * \lambda_2 \quad (5)$$

$$N_{IF}^{s,j} = N_1^{s,j} - {}^1\!/_2 * \left(\frac{\lambda_{WL}^{s,j}}{\lambda_{IF}^{s,j}} - 1\right) * \left(N_2^{s,j} - N_1^{s,j}\right) \quad (6)$$

$$\lambda_{WL} = \frac{c}{f_1 - f_2} \quad (7)$$

where N_1 and N_2 are the integer ambiguities on the two frequencies, and λ_{WL} is the wide-lane wavelength. Due to the small wavelength of the ionosphere-free combination, the ambiguity term N_{IF} cannot be treated as an integer, and must be estimated as a float. This ambiguity can be decomposed into wide-lane and narrow-lane combinations to improve the potential for ambiguity resolution (Xiao et al., 2018).

In the context of static PPP, the set of estimated parameters can be expressed as:

$$X = \left[\bar{x}, , dt_r, Z_{wet}, Grad_{NS}, Grad_{EW}, N_{r,IF}^{s,j}\right] \quad (8)$$

where, $\bar{x}$ is receiver position correction vector relative to the a priori position. dt_r is receiver clock bias. Z_{wet} is Zenith wet tropospheric delay. $Grad_{NS}$ and $Grad_{EW}$ are tropospheric delay gradients in north–south and east–west directions. $N_{r,IF}^{s,j}$ is float ambiguity values for each satellite (Ogutcu & Farhan, 2022).

3. Design of the Experiment

To assess the performance of a low-cost GNSS receiver under varying environmental conditions, two observation stations were established on the campus of the Faculty of Engineering, University of Tehran. The stations were purposefully selected to represent a range of satellite visibility and multipath error levels, thereby enabling a realistic evaluation of receiver capability in diverse urban environments. Station 1 (S1) was positioned adjacent to the wall of a tall building, modelling a semi-obstructed visibility environment with partial obstruction and moderate multipath effects and station 2 (S2) was located in a relatively open-sky area with minimal obstructions, providing near-optimal satellite visibility. Figure 1 illustrates the geographical layout of the two stations using a Google Earth image.

Figure 1. Layout of stations on a Google Earth image

At both stations, observations were conducted using a low-cost u-blox ZED-F9P dual-frequency GNSS receiver fed by low-cost ANN-MB antenna. In each case, the antenna height was carefully measured and maintained consistently throughout the observation period.

The core objective of the experiment was to evaluate the low-cost GNSS receiver's performance in static PPP technique. The assessment focused on two key metrics. First, convergence time, defined as the period required for the PPP solution to reach a high-precision, stable estimate. Second, final positional accuracy, evaluated by comparing the PPP-derived coordinates against reference positions obtained from geodetic-grade equipment.

The GNSS receiver system used in this study includes a 10 cm diameter metal ground plane, as recommended by the manufacturer, to mitigate multipath effects and enhance positioning accuracy. To evaluate the actual impact of this component on overall performance, observations were conducted at each station under two configurations: one with the receiver mounted directly on the ground plane, and the other without it. This comparative approach was designed to assess the receiver's sensitivity to multipath effects in both conditions. The configuration without the ground plane is of particular interest for dynamic or space-constrained applications, such as UAV-based surveying applications, where the integration of a ground plane may be impractical.

To ensure experimental consistency and enable valid performance comparisons across scenarios, all observations were carried out under identical hardware and software settings. The antenna was mounted on a stable tripod with a constant height, using the same antenna model and cable throughout the experiment. The elevation mask was uniformly set to 15° to exclude low-elevation satellites prone to increased noise and multipath effects, and data were sampled at a fixed rate of 1 Hz. At both of the stations, static observations were collected for an average duration of 2.5 hours per session.

Data collection and receiver configuration were carried out using u-center version 22.07, a GNSS evaluation software developed by u-blox and released in 2022. The u-blox ZED-F9P receiver requires an external power source and a computer interface for real-time data acquisition and storage. All observation sessions were recorded in raw format via this software, enabling post-processing with external tools.

For post-processing, PPP processing was performed using the GNSS-Lab Tool suite (gLAB), a software package developed by the Astronomy and Geomatics (gAGE) research group at the Technical University of Catalonia (UPC), under contract with the European Space Agency (ESA). gLAB supports advanced PPP processing and is capable of handling a wide range of GNSS corrections and formats. The selected processing parameters are presented in Table 1.

Table 1. PPP Processing Parameters

Parameter Name	Value
Adjustment Model	Kalman Filter
Epoch interval	1 s
Filter	Forward Smoothing
Elevation cut-off angle	15°
Receiver Phase Center	Off
Satellite Phase Center	Off
Ionosphere effect	Removed by IF Linear Combination
Troposphere effect	Estimated during the adjustment
Phase Windup	Corrected
Solid Earth Loading	Corrected
Relativistic Corrections	Applied
Cycle-slip	Corrected by Melborne-Wubbena combination

In this study, PPP solutions were computed using three types of IGS orbit and clock products: ultra-rapid (observed-half), rapid, and final products. The objective was to evaluate how the choice of correction product impacts positioning accuracy, particularly in environments with varying signal quality. All PPP-derived positions were then assessed against reference coordinates established using a geodetic-grade GNSS receiver to quantify accuracy under each processing scenario.

To quantitatively assess performance, two evaluation criteria were applied: precision and accuracy. Precision was measured as the standard deviation of the coordinate time series, computed from each epoch to the final epoch of the observation period. This metric provides insight into the stability and consistency of the estimated positions over time. Convergence time for precision was defined as the earliest epoch after which the coordinate standard deviation consistently remained below a defined threshold (1.5 cm in this study) for all subsequent epochs. This indicates the point at which the PPP solution stabilized and delivered repeatable, high-precision results. The final coordinate estimate for each observation scenario was then computed as the mean of all positions from the precision-based convergence time onward. To evaluate accuracy, the absolute positioning error was computed by comparing the estimated coordinates at each epoch with the reference coordinates obtained from the high-precision Hi-Target geodetic receiver. An absolute error threshold of 30 cm was adopted for acceptable positioning accuracy. Convergence time in this context was defined as the first epoch after which the absolute error consistently remained below this threshold for the remainder of the session. This definition reflects the moment at which the receiver's estimated position aligns reliably with the ground truth. By applying both precision- and accuracy-based convergence analyses, this methodology provides a robust and comprehensive assessment of the low-cost receiver's static positioning performance under real-world conditions. The selected thresholds were chosen based on commonly accepted PPP performance criteria reported in previous low-cost GNSS studies and to reflect practical positioning requirements for engineering and mapping applications.

4. Results and Discussion

The primary objective of this study was to evaluate the static positioning performance of a low-cost, dual-frequency GNSS receiver, the u-blox ZED-F9P, under varying environmental conditions. Two observation scenarios were considered to represent different levels of satellite signal obstruction and multipath error: a semi-obstructed location adjacent to a building (half-sky), and a relatively open-sky site with minimal obstruction. The analysis also investigated the impact of integrating a metallic ground plane on positioning quality, aiming to assess its effectiveness in mitigating multipath errors. Furthermore, the study compared positioning performance using different categories of IGS orbit and clock products, ultra-rapid, rapid, and final, obtained from the Center for Orbit Determination in Europe (CODE). These products were used within a PPP processing framework to determine how the availability and precision of correction data influence convergence time, positional accuracy, and overall solution stability. Additionally, results derived from the Standard Point Positioning (SPP) method are presented; this method relies primarily on code observations and broadcast navigation data without the use of precise orbit and clock corrections.

Table 2 presents a detailed summary of the horizontal positioning errors and convergence times across the two observation stations (S1 and S2), comparing scenarios with and without the metallic ground plane, and using three types of IGS orbit and clock products. Convergence times are evaluated using two criteria: (1) the epoch at which the absolute positioning error consistently remains below 30 cm (accuracy-based convergence time), and (2) the epoch at which the standard deviation of the coordinate time series falls below 1.5 cm, indicating solution stability and precision (precision-based convergence time).

Table 2. summary of the horizontal positioning errors and convergence times across the two observation stations

Station	Ground Plane	IGS Products	Error-X (m)	Error-Y (m)	2D-Error (m)	accuracy-based convergence time (s)	precision-based convergence time (s)
S1	Without Ground Plane	Ultra-Rapid	-0.642	-0.110	0.651	-	6658
		Rapid	-0.265	-0.131	0.296	6488	4228
		Final	-0.010	-0.105	0.105	1512	2622
	With Ground Plane	Ultra-Rapid	0.131	0.113	0.172	6209	6819
		Rapid	-0.069	-0.110	0.130	1019	1599
		Final	-0.041	-0.065	0.077	-	-
S2	Without Ground Plane	Ultra-Rapid	0.462	-0.292	0.547	8283	7473
		Rapid	-0.101	0.052	0.114	1563	2243
		Final	-0.040	0.009	0.041	1183	1503
	With Ground Plane	Ultra-Rapid	-0.588	0.123	0.600	-	9493
		Rapid	-0.030	0.006	0.030	1663	2623
		Final	-0.006	0.004	0.007	1973	5853

As shown in Table 2, station S1 faces partial but not complete signal obstruction due to its location adjacent to a tall building. Figure 2 presents the time series of the two-dimensional (2D) positioning error, defined as the Euclidean distance between the estimated coordinates at each epoch and the reference coordinates, for both configurations: with and without the ground plane. Figure 3 further compares the 2D error across four processing strategies: SPP, and PPP using ultra-rapid (PPP-ULT), rapid (PPP-RAP), and final (PPP-FNL) IGS products, under both ground plane conditions. The results indicate that, without the ground plane, 2D positioning errors ranged from 0.65 meters using ultra-rapid products to 0.1 meters with final products. Although convergence was achievable, it occurred slowly, with accuracy-based convergence times exceeding an hour in some cases (Table 2). As shown in Figure 2(a), the time series for S1 contains some discontinuities in the absence of the ground plane, particularly in the form of intermittent jumps that are effectively eliminated when the ground plane is used.

The inclusion of the ground plane led to consistent improvements in both accuracy and convergence time. 2D positioning errors decreased slightly across all PPP processing methods, to 0.17 m (ultra-rapid), 0.13 m (rapid), and 0.07 m (final), demonstrating the effectiveness of the IGS product type. More notably, convergence times improved substantially, especially with rapid and final products, where accuracy-based convergence time were reached in 1019 seconds, compared to significantly longer durations without the ground plane. Precision-based convergence followed a similar pattern, further confirming the benefit of improved signal quality and reduced multipath interference.

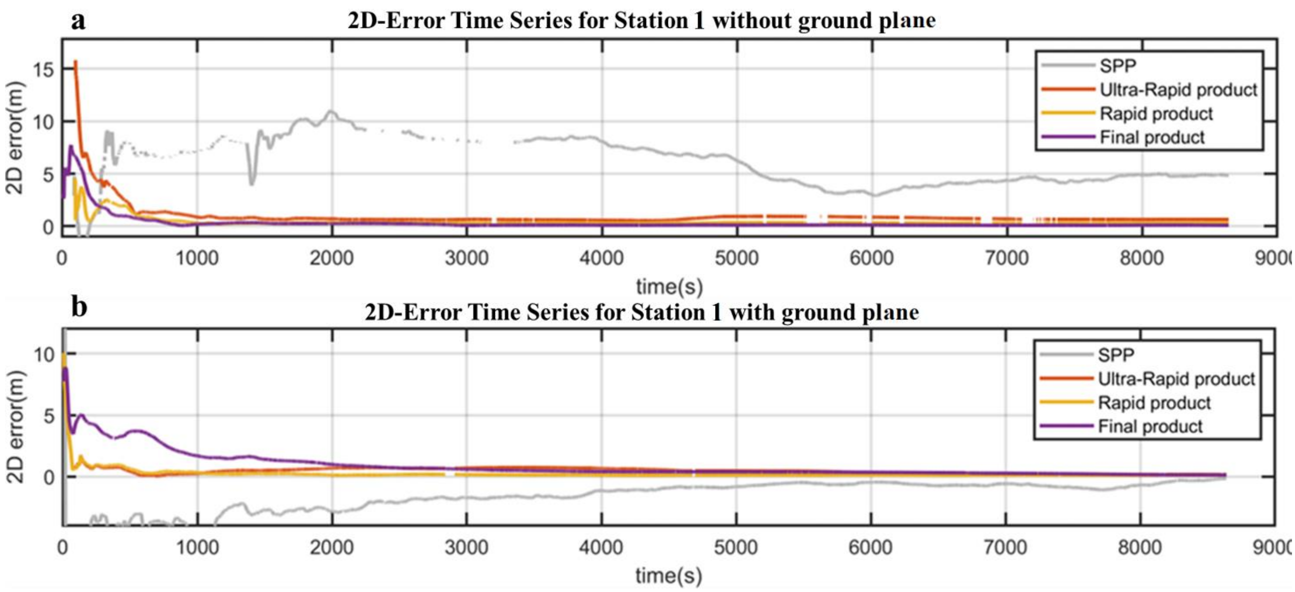

Figure 2. 2D Error time series for Station 1

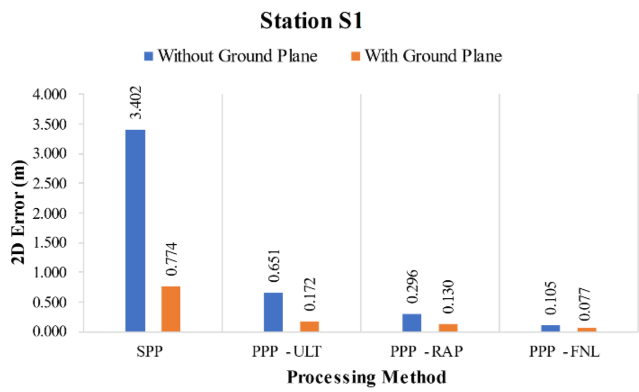

Figure 3. 2D error for various processing strategies with and without ground plane for station 1

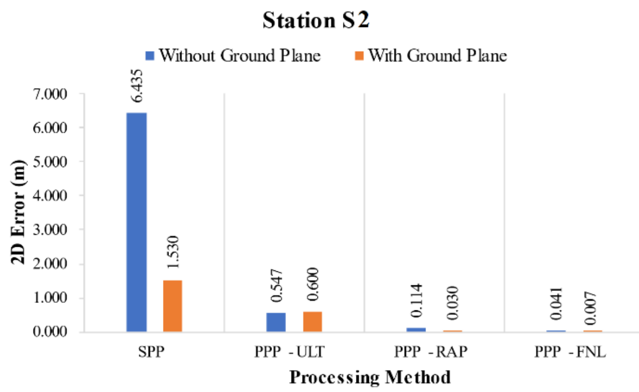

Figure 4. 2D error for various processing strategies with and without ground plane for station 2

The findings also highlight the superior performance of rapid and final IGS products over ultra-rapid ones in terms of both precision and convergence rate, with final products yielding the most consistent accuracy. This emphasizes the combined value of high-quality orbital products and physical multipath mitigation in moderately obstructed environments. Additionally, SPP performance remained at the meter-level and exhibited pronounced directional errors along the Y-axis, likely attributable to persistent building-induced multipath and the inherent limitations of code-only solutions. In contrast, this directional bias was not present in the PPP results, due to the incorporation of carrier-phase measurements, which offer significantly enhanced precision and resilience to multipath effects.

Station S2, located in an open-sky environment with minimal obstructions, exhibited the highest positioning performance across all tested scenarios. Figure 4 compares the 2D error across the various processing strategies, while Figure 5 presents the time series of the 2D positioning error for both ground plane configurations.

The results demonstrate that even without the ground plane, the final IGS products achieve a 2D error as low as 0.04 meters, with rapid convergence times, approximately 1183 seconds for accuracy-based and 1503 seconds for precision-based convergence (Table 2). When the ground plane is incorporated, performance improves further, 2D positioning errors drop to ~3 cm with rapid products and as low as ~1 cm with final products, effectively reaching centimeter-level accuracy.

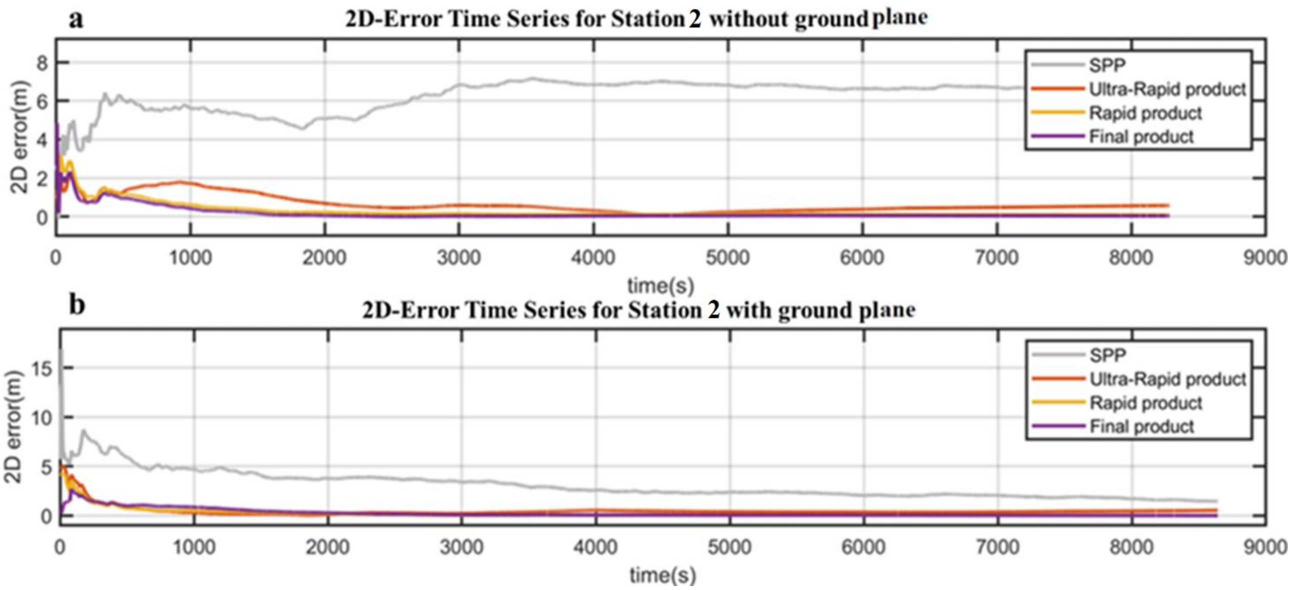

Figure 5. 2D Error time series for Station 2

Unlike Stations S1, the time series for S2 displays no significant discontinuities and is characterized by minimal bias in both coordinate components (Figure 5). This consistency reflects the favourable signal conditions at the site and the negligible impact of multipath or obstruction-related distortions. The findings underscore that, under open-sky conditions, the low-cost GNSS receiver, when paired with precise orbital products and a ground plane, can achieve high-precision results comparable to those of professional-grade equipment.

Although the results demonstrate promising performance, the experiments were limited to static observations at two urban stations and may not fully represent more challenging kinematic or heavily obstructed environments.

Overall, the results highlight the critical influence of environmental conditions, antenna configuration (the use of a ground plane), and GNSS correction product quality on the positioning performance of low-cost dual-frequency receivers. In semi-obstructed urban environments (S1), multipath and signal blockage degraded accuracy and the convergence time; although using the metal ground plane and high-precision orbit and clock products have improved the receiver function. In contrast, at open-sky (S2) sites, the receiver demonstrated substantial improvements in both accuracy and convergence when a ground plane was employed, particularly in combination with rapid and final IGS products. The final products consistently outperformed ultra-rapid and rapid solutions in terms of precision, although rapid products provided a favourable balance between accuracy and shorter convergence times. Furthermore, while SPP remained limited to meter-level accuracy, PPP solutions, especially under optimal conditions, achieved centimeter-level performance. These findings support the capability of low-cost GNSS receivers for high-precision applications; allow for more efficient deployment strategies, balancing cost and performance based on environmental demands.

5. Conclusion

This study evaluated the static Precise Point Positioning (PPP) performance of the low-cost dual-frequency u-blox ZED-F9P GNSS receiver under two observational environments representing different levels of signal obstruction and multipath interference: a semi-obstructed (half-sky) environment and an open-sky environment. The analysis also investigated the influence of a metallic ground plane and different categories of IGS orbit and clock products (ultra-rapid, rapid, and final) on positioning accuracy, convergence time, and solution stability.

The results demonstrate that, among the tested factors, environmental conditions exerted the greatest influence on positioning performance. In the semi-obstructed environment, signal blockage and multipath effects significantly degraded positioning accuracy and the speed of PPP convergence time. However, the use of a metallic ground plane consistently improved solution stability and reduced positioning errors by mitigating reflected signals. In open-sky conditions, the receiver achieved centimeter-level positioning accuracy when processed with rapid and final IGS products, while sub-decimetre accuracy was obtained under semi-obstructed conditions.

The study also confirmed the importance of precise orbit and clock products in PPP applications. Final IGS products provided the highest positioning accuracy and the most stable solutions, whereas rapid products offered a practical balance between positioning performance and product availability. In contrast, Standard Point Positioning (SPP), which primarily relies on code observations and broadcast navigation data, remained limited to meter-level accuracy across all tested scenarios and was therefore unsuitable for applications requiring high positional precision.

The findings demonstrate that low-cost dual-frequency GNSS receiver can provide reliable high-precision positioning for cost-sensitive geospatial applications when appropriate processing strategies and observation conditions are employed.

Nevertheless, the experiments were limited to static observations conducted at two stations using a single receiver–antenna configuration and one analysis center product source. Therefore, the findings may not fully represent more challenging urban canyon environments or dynamic positioning applications. Future research should investigate the performance of low-cost GNSS receivers using a larger number of observation stations, kinematic scenarios, and dense urban environments. In addition, more advanced PPP techniques, such as PPP-AR and PPP-RTK, should be evaluated to further assess ambiguity fixing performance, convergence behaviour, and positioning stability in low-cost GNSS applications.

6. References

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