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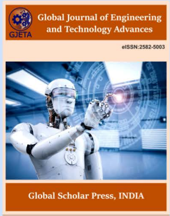

(Research Article)

Kinematic PPP in Free-Multipath Open-Sky: CSRS-PPP Vs. Qinertia Cloud

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Abstract

This study evaluates and compares the performance of kinematic Precise Point Positioning (PPP) using two freely available online processing services, namely the Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP) and Qinertia Cloud, under open-sky conditions with negligible multipath effects. Dual-frequency GNSS observations collected continuously for 24 hours from ten well-distributed reference stations across Libya were processed under two configurations: GPS-only and combined GPS+GLONASS. The performance assessment was carried out using several statistical indicators, including the Average Absolute Error (AAE), Maximum Absolute Error (MAE), Root Mean Square Error (RMSE), and the percentage of gross errors exceeding 5 cm in the horizontal components and 10 cm in the height component. The results demonstrate that both services are capable of delivering reliable centimeter-level kinematic PPP solutions, while the integration of GLONASS observations generally improves positioning accuracy and solution reliability. CSRS-PPP exhibits the best overall performance under both processing configurations, achieving RMSE and AAE values below 2 cm in all coordinate components and eliminating gross errors entirely in the combined GPS+GLONASS solution. In addition, the maximum absolute errors obtained from CSRS-PPP remain limited to approximately 10 cm and 7 cm for GPS-only and GPS+GLONASS processing, respectively. Qinertia Cloud also provides high-quality solutions, particularly when multi-constellation processing is employed. The integration of GLONASS reduces the RMSE values in the East, North, and Height components from approximately 2.5 cm, 4 cm, and 6.5 cm to about 2 cm, 1.5 cm, and 2 cm, respectively, while significantly decreasing the percentage of gross errors and reducing the maximum absolute errors in all coordinate components. Overall, the comparative analysis confirms the effectiveness of multi-constellation GNSS processing for improving kinematic PPP performance through enhanced satellite geometry and increased observation redundancy. Although both online services provide accurate and reliable solutions suitable for high-precision kinematic applications, CSRS-PPP demonstrates slightly superior consistency and robustness, whereas Qinertia Cloud offers competitive centimeter-level performance, particularly when GPS and GLONASS observations are combined.

Keywords: GPS; GLONASS; Kinematic PPP; Open Sky; Free-Multipath; CSRS-PPP; Qinertia Cloud

1. Introduction

Global Navigation Satellite Systems (GNSS), such as the Global Positioning System (GPS) and the Russian Global Navigation Satellite System (GLONASS), are space-based positioning infrastructures that enable the determination of position and velocity through passive ranging observations [1]. The two systems operate continuously and independently of weather conditions [2], providing precise real-time positioning and timing services on a global scale [3]. These systems rely on satellite constellations that broadcast signals on two principal frequencies, modulated using Coarse/Acquisition (C/A) and Precise (P) codes [4]. From these signals, GNSS receivers derive pseudo-range and carrier-phase measurements, which form the foundation of modern navigation, mapping, and geodetic applications [5]. The achievable positioning accuracy depends on several factors, including satellite geometry, atmospheric effects, and

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receiver characteristics [6]. The two systems are different in number of orbital planes, altitude, number of satellites, inclination angles, and frequency as illustrated in the table below.

Table 1 Comparison Between GPS and GLONASS

Feature	GPS	GLONASS
Full Constellation	~31 satellites	~24 satellites
Orbital Planes	6	3
Orbit Altitude	~20,200 km	~19,100 km
Inclination Angle	55°	64.8°
Frequencies	L1, L2, L5	L1, L2, L3
Time Reference	GPS Time	GLONASS Time (UTC-based)
Coordinate System	WGS84	PZ-90
Global Coverage	Excellent	Excellent (better at high latitudes)
Accuracy (Standalone)	High	Comparable (varies with geometry)
Strengths	Stable, widely used, strong global infrastructure	Better performance at high latitudes, faster geometry variation
Weaknesses	Slightly weaker geometry at high latitudes	Frequency-dependent biases, less common in older receivers

Positioning techniques based primarily on code measurements typically provide meter-level accuracy [7,8], which is sufficient for applications with moderate precision requirements, such as ground vehicle navigation [9], unmanned aerial vehicle (UAV) operations [10], and the generation of low-accuracy ortho-mosaics and digital elevation models [11]. In contrast, high-precision applications, including geodetic control, deformation monitoring, and precision engineering, require centimetre-level accuracy [12]. Such performance can be achieved using advanced processing techniques, notably Differential GNSS (DGNSS) and Precise Point Positioning (PPP) [13].

DGNSS enhances positioning accuracy by combining simultaneous observations from a reference station with known coordinates and a rover receiver at an unknown location [14]. The use of single-, double-, or triple-differenced observations effectively reduces common error sources, such as satellite clock biases and ionospheric delays [15]. Dual-frequency DGNSS systems can achieve millimetre-level accuracy, while single-frequency systems typically provide decimetre-level precision at lower cost. However, the requirement for a nearby reference station limits the applicability of DGNSS, particularly in large-scale or remote regions [16].

Precise Point Positioning (PPP) provides a globally applicable technique that enables high-accuracy positioning without the need for local reference stations [17]. It relies on precise satellite orbit and clock products, typically provided by the International GNSS Service (IGS), combined with rigorous modelling of atmospheric, relativistic, and geophysical effects [18]. Under favourable conditions, PPP can achieve centimetre-level accuracy in both static and kinematic modes; however, it generally requires longer convergence times compared to Differential GNSS (DGNSS) [19]. Among available online PPP processing platforms, the CSRS-PPP and Qinertia Cloud free services are widely utilized, providing coordinate solutions referenced to various datums supporting. Both services support GPS-only and combined GPS+GLONASS configurations. Users can upload dual-frequency RINEX observation files, after which the services automatically apply precise ephemerides, clock corrections, and atmospheric models to generate final positioning solutions. The performance of PPP is influenced by several factors, including satellite availability and geometry, multipath effects, antenna characteristics [20], atmospheric modelling [21], and the quality of precise orbit and clock products (ultra-rapid, rapid, or final) [22,23].

In this study, the performance of static PPP is evaluated using the CSRS-PPP as well as Qinertia Cloud services with final precise ephemerides under open-sky conditions to minimize multipath effects. Dual-frequency observations were collected from ten well-distributed stations, each observed continuously for 24 hours. Data were processed in kinematic mode using GPS-only and combined GPS+GLONASS configurations. The 24-hour static solutions were adopted as reference coordinates to assess the accuracy of shorter observation durations. Despite extensive research on PPP, further investigation remains necessary. Many previous studies do not fully isolate the impact of multipath, and PPP accuracy is often assessed using DGNSS-derived coordinates, which may themselves be affected by multipath, weak satellite geometry, long baselines, or height differences between reference and rover stations. Moreover, continuous advancements in GNSS constellations and processing strategies necessitate regular re-evaluation of positioning techniques. This study forms part of ongoing efforts at the University of Benghazi to evaluate widely used free PPP and DGNSS online services in both static and kinematic modes, including CSRS-PPP [16,17], PPP-WIZARD [18,19], APPS [20,21], magic-GNSS [24], Trimble RTX-PP [25], and Qinertia Cloud [14,15]. Future work will extend this research to multipath-rich environments, as well as to the integration of PPP with MEMS-based inertial navigation systems and vision-based navigation techniques. Additional efforts will also focus on improving PPP performance for drone-based surveying to reduce processing time in automated image-matching workflows. Related studies conducted at the University of Benghazi are presented in [26-30].

2. Objectives and methodology

The primary objective of this study is to assess the advantages of integrating GLONASS observations with GPS for kinematic PPP using dual-frequency data under open-sky conditions. The analysis focuses on solutions obtained from the CSRS-PPP and Qinertia Cloud free online services using final precise ephemerides. This topic merits further investigation, as a considerable portion of existing research evaluates kinematic PPP performance without fully mitigating multipath effects. Additionally, many previous studies assess kinematic PPP accuracy by comparing PPP-derived solutions with DGNSS coordinates obtained from real-time or post-processed kinematic measurements. Such comparisons may introduce uncertainties, since DGNSS solutions can themselves be affected by multipath, unfavourable satellite geometry, extended baseline lengths, or height differences between reference and rover stations. In contrast, the present study emphasizes the analysis of outlier reduction achieved by incorporating GLONASS observations into GPS-alone kinematic PPP solutions. This methodology provides clearer insight into the benefits of multi-constellation GNSS processing under conditions free from multipath effects, poor dilution of precision, and low-quality satellite ephemerides associated with ultra-rapid and rapid products.

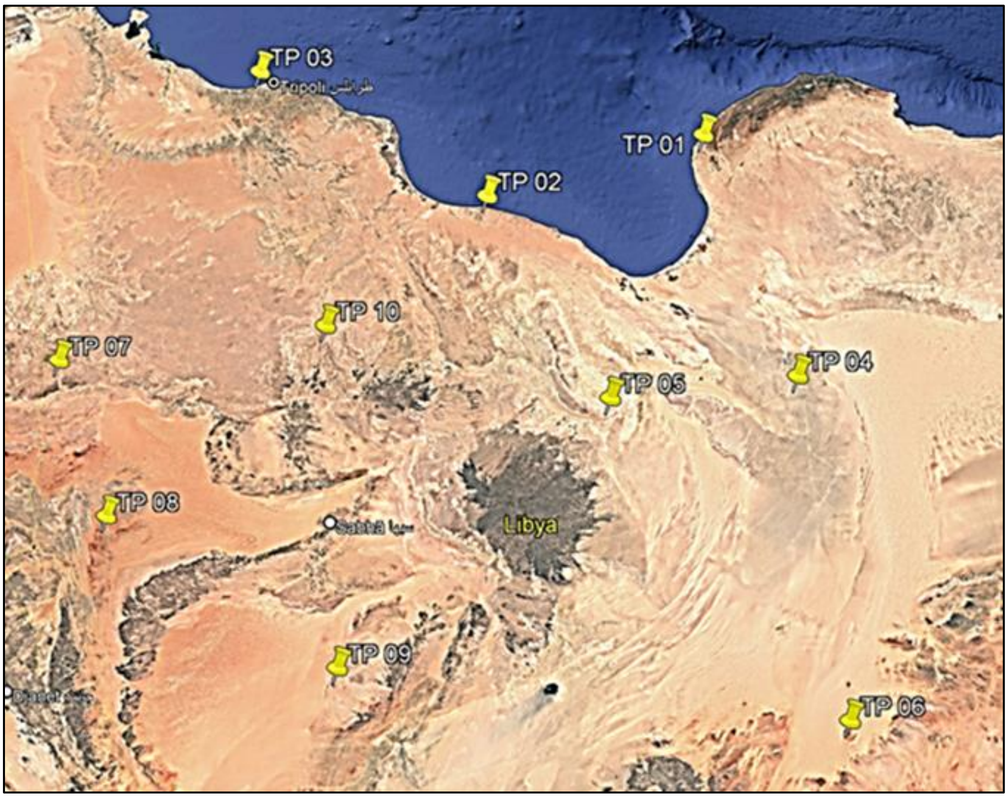

Figure 1 Testing points distribution across Libya

The dataset employed in this study was obtained through the Engineering Consultancy Office of Benghazi University and originates from multiple projects conducted across different regions of Libya. Ten independent datasets were collected using a dual-frequency GNSS receiver operating in static mode under clear open-sky conditions, with each observation session lasting 24 consecutive hours. For each site, the acquired observations will initially be processed using static mode with final precise products to derive high-accuracy reference coordinate solutions. The 24-hours static results obtained from the two services will be compared to the reference coordinates of these points that provided by the Libyan Survey Department and approved by the oil fields in which these points are located. If the static coordinates of each service match the reference coordinates, this means that the processing of this service is clear from systematic errors, and if not, the value of the fixed systematic error will be taken into account when evaluating the kinematic solutions. After that, the same datasets will subsequently be reprocessed in kinematic mode and compared with their corresponding static reference coordinates to quantify positioning performance. The assessment metrics will include the Average Absolute Error (AAE), the Root Mean Square Error (RMSE) of the residuals, the Maximum Absolute Error (MAE), and the percentage of outlier epochs exceeding predefined thresholds of 5 cm in the horizontal components (Easting and Northing) and 10 cm in the vertical component (Height). The use of observation points that are spatially well distributed throughout Libya enables an investigation of the influence of station location and satellite geometry on the accuracy and stability of the derived positioning results. Figure (1) shows the distribution of testing points across Libya.

3. Results and discussion

Table (2) includes the values of Average Absolute Error (AAE), Maximum Absolute Error (MAE), Route Mean Square Error (RMSE), and the percentage of outliers exceeding 5 cm in the Easting and Northing components and 10 cm in the Height component of the results of the three compared services. Then, sample of the quality of E, N, H, as 2D differences in GPS-alone & GPS+GLONASS from one site for each service are shown. Starting with CSRS-PPP, figures (2) to (4) show the quality of all components of testing point (TP 01), located in Benghazi University main campus. Then Qinertia Cloud, figures (5) to (7) show the quality of all components of testing point (TP 08), located in Atshan Oil Field.

Table 2 The final results of statistical analysis for all points

Service	Indicator	GPS-ALONE			GPS+GLONASS		
		E	N	H	E	N	H
CSRS-PPP	AAE mm	5.88	6.97	17.6	5.17	6.03	14.52
	MAE mm	34.5	44.2	80.23	25.3	30	63
	RMSE mm	6.11	6.89	14.8	5.46	5.79	9.04
	Outlier %	0%	0%	0%	0%	0%	0%
Qinertia Cloud	AAE mm	20	22	40	20	12	23
	MAE mm	130	220	300	50	130	170
	RMSE mm	20	40	65	20	15	20
	Outlier %	8%	5%	5%	2%	1%	1%

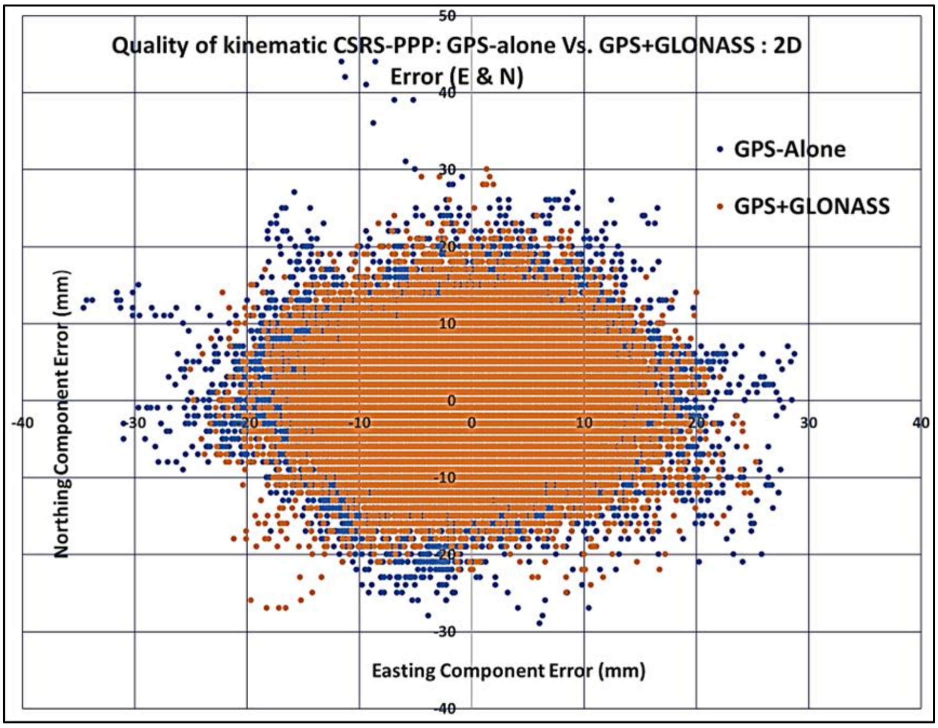

Figure 2 CSRS-PPP: 2D Quality (E & N): GPS-alone Vs. GPS+GLONASS

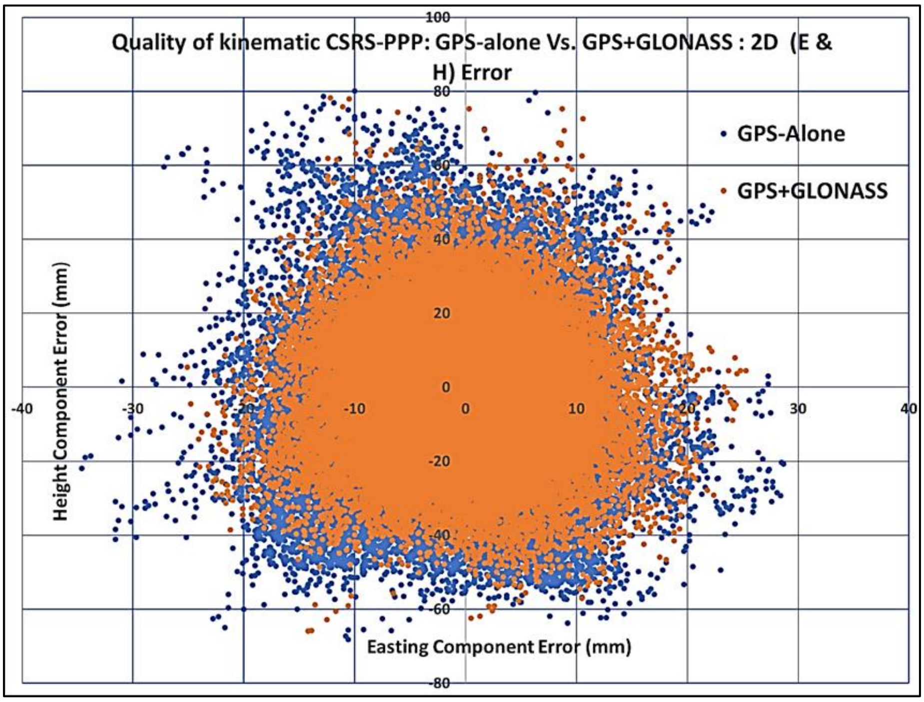

Figure 3 CSRS-PPP: 2D Quality (E & H): GPS-alone Vs. GPS+GLONASS

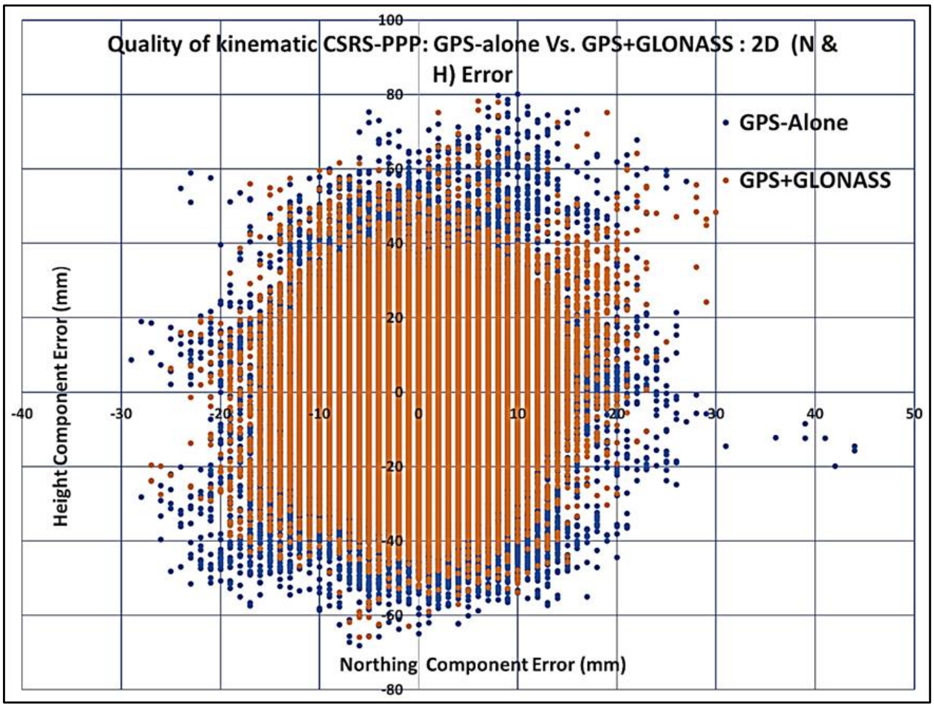

Figure 4 CSRS-PPP: 2D Quality (N & H): GPS-alone Vs. GPS+GLONASS

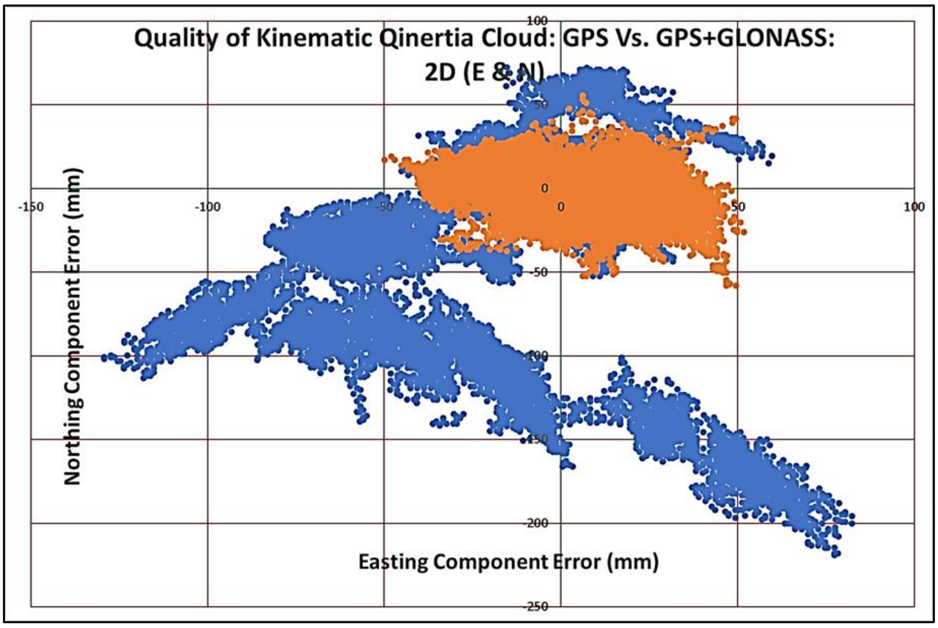

Figure 5 Qinertia Cloud: 2D Quality (E & N): GPS-alone Vs. GPS+GLONASS

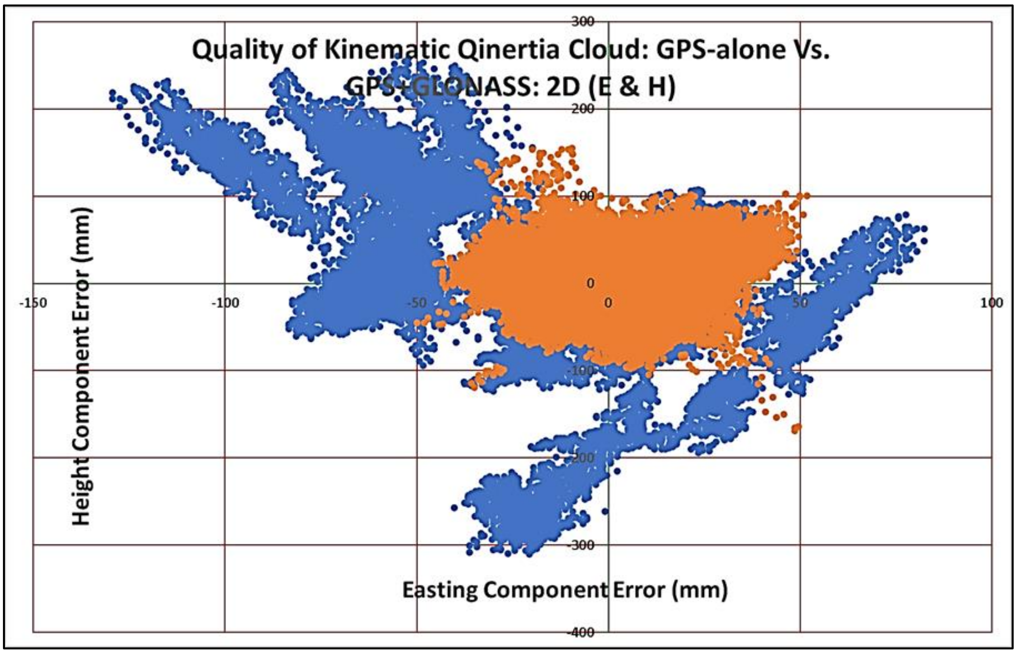

Figure 6 Qinertia Cloud: 2D Quality (E & H): GPS-alone Vs. GPS+GLONASS

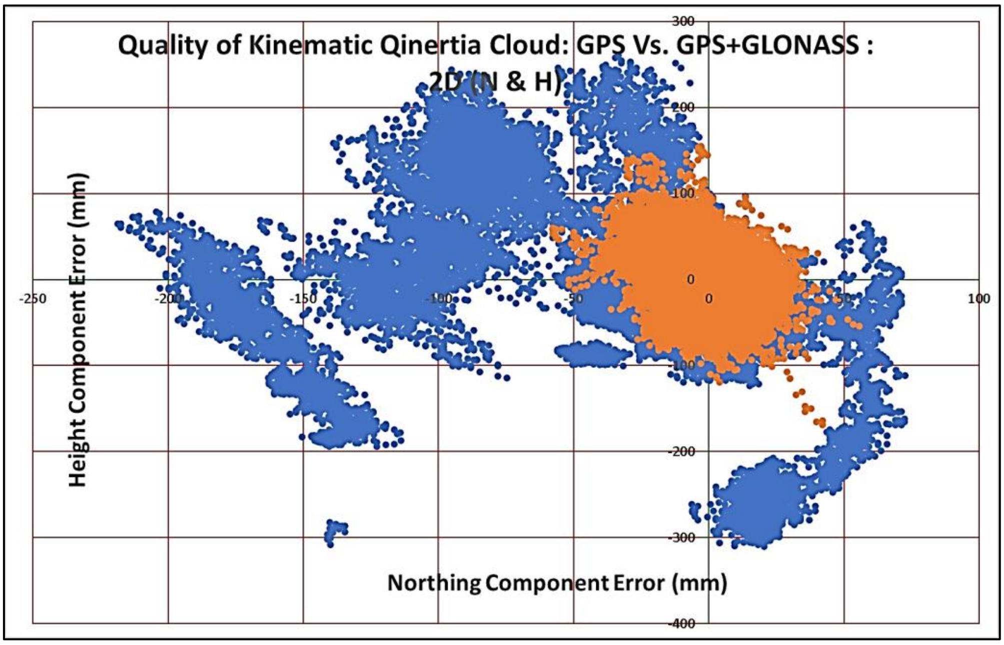

Figure 7 Qinertia Cloud: 2D Quality (N & H): GPS-alone Vs. GPS+GLONASS

The results demonstrate that both Qinertia Cloud and CSRS-PPP are capable of delivering reliable kinematic PPP solutions with centimeter-level accuracy under both GPS-only and GPS+GLONASS processing strategies. Nevertheless, CSRS-PPP exhibits superior overall stability and robustness, particularly under GPS-only processing. The service provides highly stable and continuous solutions with RMSE values generally below 2 cm in all coordinate components and without any detected outliers exceeding the adopted thresholds of 5 cm in the horizontal components and 10 cm in height. In comparison, Qinertia Cloud also produces accurate and continuous positioning solutions suitable for most engineering applications; however, slightly larger RMSE values and a higher percentage of outliers are observed under GPS-only processing.

The integration of GLONASS observations improves the performance of both systems. For Qinertia Cloud, the inclusion of GLONASS observations reduces the RMSE values in the East, North, and Height components from approximately (2 cm, 4 cm, and 6.5 cm) to about (2 cm, 1.5 cm, and 2 cm), respectively. Similarly, CSRS-PPP demonstrates noticeable improvements in positioning consistency and reliability when GLONASS observations are integrated, with enhancements of approximately 13% in the East component, 15% in the North component, and 21% in the Height component. In both services, the multi-constellation approach also reduces the frequency and magnitude of gross errors and improves the overall robustness of the positioning solution.

A comparison of the maximum absolute errors further highlights the stability of CSRS-PPP solutions. While Qinertia Cloud produces maximum absolute errors of approximately (13 cm, 22 cm, and 30 cm) under GPS-only processing, decreasing to (5 cm, 13 cm, and 17 cm) after integrating GLONASS observations, CSRS-PPP maintains significantly lower maximum three-dimensional errors, remaining below 10 cm for GPS-only solutions and below 7 cm for GPS+GLONASS processing. These results indicate that CSRS-PPP is less sensitive to unfavorable observation conditions and better able to suppress large positioning deviations.

The observed improvements achieved through GPS+GLONASS integration can primarily be attributed to the increased number of tracked satellites and the resulting enhancement in satellite geometry. Improved geometry leads to lower dilution of precision (DOP) values, thereby strengthening the positioning solution, particularly during periods of limited GPS satellite availability. In addition, the larger number of observations increases redundancy within the mathematical adjustment model, allowing more effective detection and mitigation of measurements affected by large residuals. The availability of additional satellites also enables the exclusion of low-elevation observations, which are generally associated with higher atmospheric noise and lower measurement quality. Consequently, both Qinertia Cloud and CSRS-PPP benefit significantly from multi-constellation processing in terms of positioning accuracy, reliability, and robustness.

Overall, the findings confirm that both Qinertia Cloud and CSRS-PPP can provide high-quality kinematic PPP solutions suitable for precise engineering and geodetic applications. However, CSRS-PPP demonstrates superior stability, lower sensitivity to outliers, and more consistent positioning performance, while Qinertia Cloud remains highly competitive and shows substantial improvement when GLONASS observations are incorporated.

4. Conclusions

This study presented a comprehensive evaluation of kinematic Precise Point Positioning (PPP) performance using two freely available online processing services, namely CSRS-PPP and Qinertia Cloud, under controlled open-sky conditions with negligible multipath effects. Dual-frequency GNSS observations collected from ten well-distributed stations across Libya were processed using both GPS-only and combined GPS+GLONASS configurations in order to investigate the influence of multi-constellation integration on positioning accuracy, reliability, and robustness. The results confirm that both services are capable of delivering continuous centimetre-level kinematic PPP solutions suitable for a wide range of precise engineering and geodetic applications. Nevertheless, clear differences in performance were observed between the two processing platforms. CSRS-PPP consistently demonstrated the highest level of stability and reliability, achieving RMSE and AAE values below 2 cm in all coordinate components and completely eliminating gross errors in the combined GPS+GLONASS configuration. Furthermore, the maximum absolute errors associated with CSRS-PPP remained limited to only a few centimetres, indicating a highly robust and stable positioning solution even under single-constellation processing.

Qinertia Cloud also produced highly competitive results, particularly when GPS and GLONASS observations were integrated. The inclusion of GLONASS significantly improved the quality of the kinematic PPP solution by reducing RMSE values, minimizing the occurrence of gross errors, and decreasing the magnitude of maximum positioning deviations in all coordinate components. These improvements primarily result from the increased number of available satellites, enhanced satellite geometry, and greater observation redundancy, which collectively strengthen the mathematical adjustment model and improve the capability to detect and mitigate low-quality observations. The comparative analysis further highlights the importance of multi-constellation GNSS processing in modern PPP applications. The integration of GLONASS observations substantially enhances positioning consistency and robustness for both investigated services, particularly during periods of limited satellite visibility or unfavourable geometry. The findings also demonstrate that relying solely on a single GNSS constellation is becoming increasingly less favourable for high-precision kinematic applications, especially when robust and continuous positioning solutions are required.

Overall, the study confirms that both CSRS-PPP and Qinertia Cloud constitute effective and reliable tools for high-accuracy kinematic PPP processing. However, CSRS-PPP exhibits superior overall consistency, lower sensitivity to outliers, and enhanced robustness, while Qinertia Cloud remains a strong alternative capable of achieving high-quality centimetre-level solutions when multi-constellation observations are employed.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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