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Dual-Frequency Kinematic PPP in Free-Multipath Open-Sky: CSRS-PPP vs. PPP-WIZARD Vs. APPS

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Abstract: This study assesses the performance of kinematic Precise Point Positioning (PPP) using three freely available online services: the Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP), PPP-WIZARD, and the Automatic Precise Positioning Service (APPS). The evaluation was carried out under open-sky conditions to minimize multipath effects and considered two processing configurations, namely GPS-alone and GPS+GLONASS. Dual-frequency GNSS observations were collected at 10 spatially well-distributed reference points across Libya, with each station observed continuously for 24 hours and processed in kinematic mode. The performance evaluation relied on four statistical indicators: Average Absolute Error (AAE), Maximum Absolute Error (MAE), Root Mean Square Error (RMSE), and the percentage of outliers exceeding 5 cm in the Easting (E) and Northing (N) components and 10 cm in the Height (H) component. The results indicate that the integration of GLONASS with GPS generally leads to improvements in GPS-only kinematic PPP solutions and a marked reduction in the percentage of gross errors. These improvements are slight in case of CSRS-PPP and considerable with PPP-WIZARD. Among the evaluated services, CSRS-PPP demonstrates the best overall performance, achieving 0% outliers, AAE and RMSE values below 2 cm in all coordinate components, and 3D-MAE values of approximately 10 cm and 7 cm for GPS-alone and GPS+GLONASS processing, respectively. PPP-WIZARD ranks second, with the multi-constellation solution reducing RMSE values in the E, N, and H components by approximately 9 cm, 15 cm, and 42 cm, respectively, and decreasing the proportion of outliers by about 25%, 7.5%, and 11.5%, in the same order. In addition, the AAE and MAE of kinematic PPP-WIZARD solutions decrease significantly in the E, N, and H components by approximately 1 m, 2.2 m, and 2.8 m, respectively, when integrated constellations are employed. APPS, which supports GPS observations only, exhibits the lowest accuracy and the highest proportion of outliers, even when compared with GPS-only solutions from CSRS-PPP and PPP-WIZARD. Specifically, APPS produces 3D-AAE, 3D-MAE, and 3D-RMSE values of approximately 0.65 m, 3.5 m, and 0.63 m, respectively, with outlier percentages of 64% in E, 38% in N, and 45% in H. Overall, the findings clearly demonstrate the significant advantages of multi-constellation GNSS processing over single-system approaches, particularly in terms of increased observation redundancy, improved satellite geometry, and enhanced capability to mitigate weak or unreliable measurements. The comparative analysis confirms that CSRS-PPP delivers the most reliable performance under both GPS-alone and GPS+GLONASS configurations, with a slight advantage observed for the latter. PPP-WIZARD provides the second-best performance, achieving acceptable accuracy under multi-constellation processing and thus meeting the requirements of certain engineering applications that demand decimeter-level precision. In contrast, the GPS-only PPP-WIZARD and APPS kinematic solutions remain unstable, less precise, and characterized by a high proportion of gross errors.
***Keywords*: GPS; GLONASS; Kinematic PPP; Open Sky; Free-Multipath; CSRS-PPP; PPP-WIZARD; APPS.**

I. INTRODUCTION

Global Navigation Satellite Systems (GNSS), including the Global Positioning System (GPS) and Russia's Global Navigation Satellite System (GLONASS), are satellite-based navigation and positioning systems that enable the determination of instantaneous position and velocity using passive range measurements [1]. GNSS operate continuously under all weather conditions and provide high-accuracy, real-time positioning and timing information on a global scale [2]. These systems rely on constellations of satellites transmitting signals on two primary frequencies, each modulated with Coarse/Acquisition (C/A) and Precise (P) codes [3]. The transmitted signals allow GNSS receivers to derive pseudo-range and carrier-phase observations, which constitute the foundation of modern navigation and geodetic surveying applications [4]. The accuracy of GNSS positioning is influenced by several factors, including satellite geometry, atmospheric propagation delays, and receiver quality [5]. Code-based positioning generally achieves accuracies at the meter level, which is adequate for low-precision applications such as vehicle navigation [6,7], drone operations [8], and the generation of low-accuracy ortho-mosaic images and digital elevation models [9,10].

In contrast, high-precision applications, including geodetic control, deformation monitoring, and precision engineering, require centimetre-level accuracy. Such accuracy can be attained using advanced techniques such as Differential carrier-phase GNSS (DGNSS) and Precise Point Positioning (PPP) [11].

DGNSS enhances positioning accuracy by utilizing simultaneous observations from a reference base station with known coordinates and a rover receiver at an unknown location [12]. Through the formation of single-, double-, or triple-differenced observations, many common GNSS error sources, including satellite clock errors and ionospheric delays, are effectively reduced [13]. Dual-frequency DGNSS configurations are capable of achieving millimetre-level accuracy, whereas single-frequency systems typically provide decimetre-level precision at substantially lower cost [14,15]. Despite its high accuracy, DGNSS requires proximity to a reference station, which limits its applicability on a global scale. Conversely, PPP represents a globally applicable alternative that does not depend on local reference stations. PPP employs precise satellite orbit and clock products, usually provided by the International GNSS Service (IGS), in addition to comprehensive models accounting for atmospheric and relativistic effects. PPP is capable of delivering centimetre-level accuracy in both static and kinematic modes, although it generally requires longer convergence times compared to DGNSS [16].

This study evaluates three widely used free online PPP processing services, namely the Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP) service, PPP-WIZARD, and the Automatic Precise Positioning Service (APPS). CSRS-PPP, developed by Natural Resources Canada (NRCan), supports both static and kinematic GNSS data processing and provides coordinate solutions referenced to the International Terrestrial Reference Frame (ITRF) [3,4]. PPP-WIZARD is a zero-difference PPP ambiguity resolution technique developed by the French governmental space agency CNES. It also supports static and kinematic GNSS datasets and delivers coordinate solutions referenced to the International Terrestrial Reference Frame (ITRF2020) [5,11]. APPS processes GPS-only observation files and applies state-of-the-art GPS PPP algorithms developed by the NASA Jet Propulsion Laboratory. APPS supports both static and kinematic datasets and provides coordinate solutions referenced to the GRS80 geodetic reference frame [12,16]. Across all three services, users may upload RINEX files from dual-frequency GNSS receivers, after which precise satellite ephemerides, clock corrections, and atmospheric models are automatically applied to generate high-quality positioning solutions. The performance of kinematic PPP is influenced by several factors, including the number of observed satellites, the surrounding multipath environment, satellite constellation availability, GNSS antenna type and quality [17], ionospheric and tropospheric delay modelling, and the type of precise satellite ephemerides employed (ultra-rapid, rapid, or final) [3].

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, PPP-WIZARD, and APPS 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.

The findings of this research will be extended in future work to investigate the impact of multipath-rich environments, the integration of kinematic PPP with Micro-Electro-Mechanical Systems (MEMS)-based Inertial Navigation Systems (INS), GPS delta positioning, and vision-based navigation techniques. Future studies will also focus on improving kinematic PPP performance in drone-based surveying applications, with the aim of enhancing the accuracy of exterior orientation parameters for aerial imagery and reducing processing time in automated image-matching workflows. Additional details on related research conducted at Benghazi University in the fields of drone-based surveying and the enhancement of automatic image matching for vision-based navigation can be found in [18–23].

II. OBJECTIVES & METHODOLOGY

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 three 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.

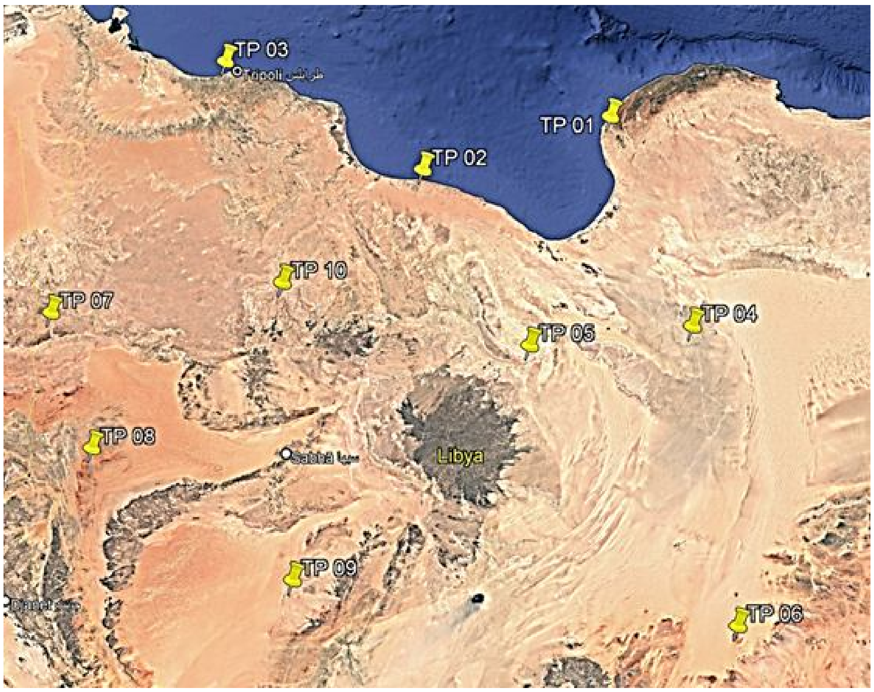

Fig. 1 Testing points distribution across Libya.

III. RESULTS & DISCUSSION

Table (1) 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, 2D & 3D differences in GPS-alone & GPS+GLONASS from one site for each service are shown. Starting with CSRS-PPP, figures (2) to (7) show the quality of all components of testing point (TP 01), located in Benghazi University main campus. Then PPP-WIZARD, figures (8) to (13) show the quality of all components of testing point (TP 08), located in Atshan Oil Field. After that, figures (14) to (19) illustrate the quality of APPS solution in all components for testing point (TP 05), located in North Waha Oil Field.

TABLE I
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%

PPP-WIZARD	AAE mm	60	42	130	20	12	23
	MAE mm	1200	2600	3200	140	420	370
	RMSE mm	110	170	440	20	15	20
	Outlier %	33%	8%	12%	8%	0.3%	0.35%
APPS	AAE mm	420	175	485	#	#	#
	MAE mm	2200	1400	2300	#	#	#
	RMSE mm	500	215	315	#	#	#
	Outlier %	64%	38%	45%	#	#	#

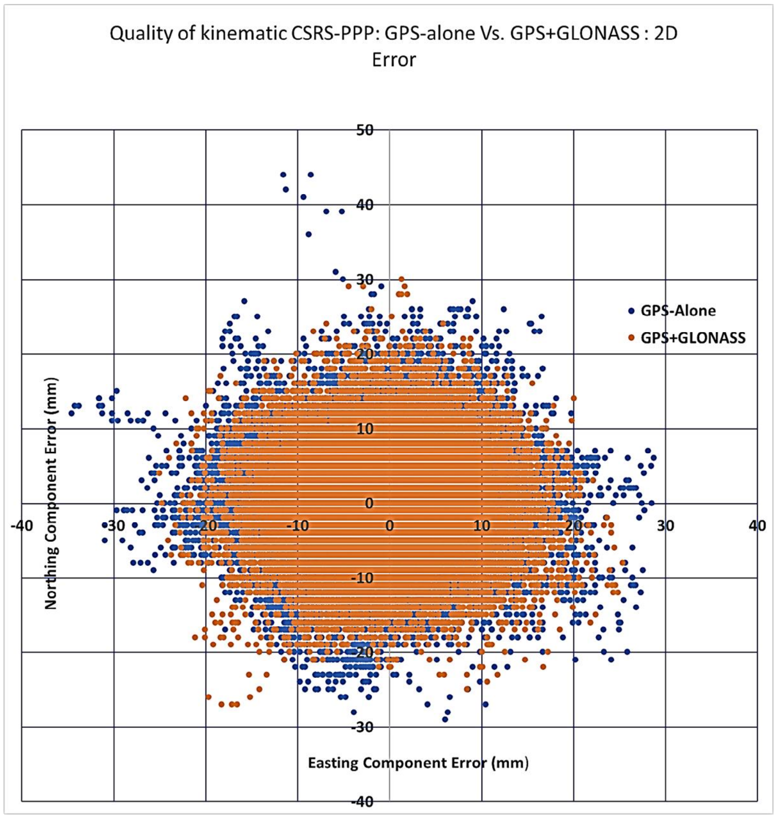

Fig. 2 CSRS-PPP: 2D Quality: GPS-alone Vs. GPS+GLONASS

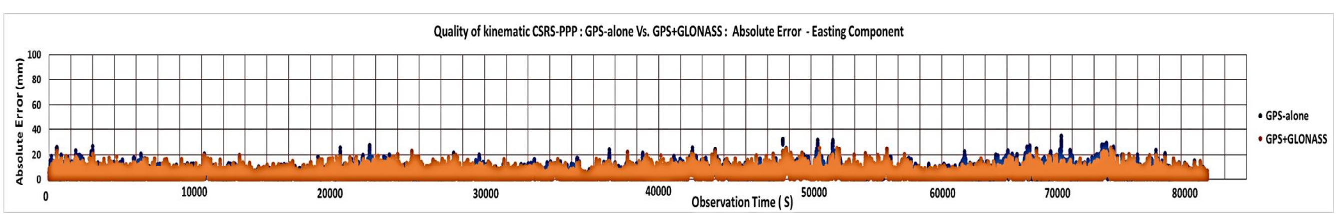

Fig. 3 CSRS-PPP: Easting Quality: GPS-alone Vs. GPS+GLONASS

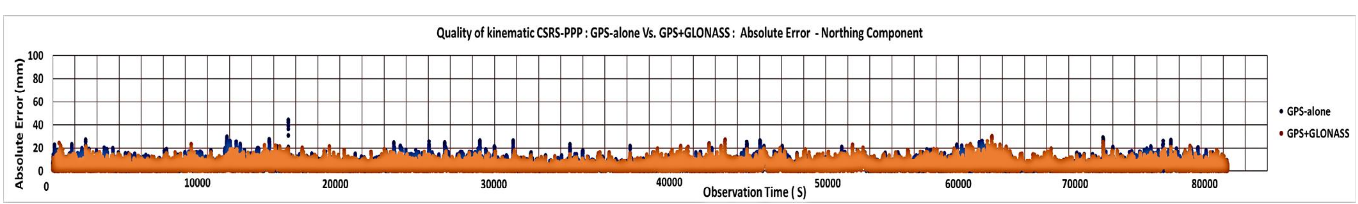

Fig. 4 CSRS-PPP: Northing Quality: GPS-alone Vs. GPS+GLONASS

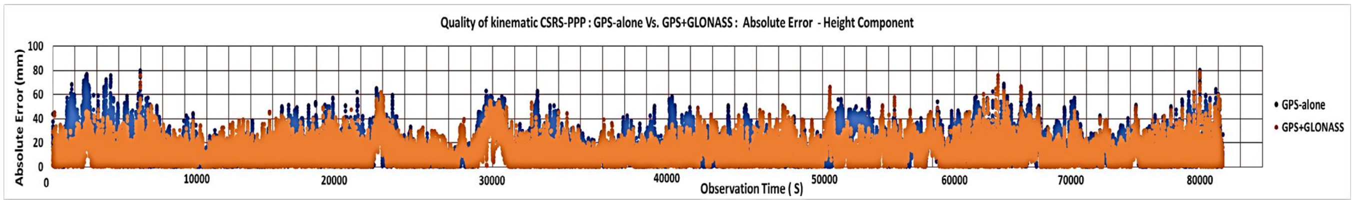

Fig. 5 CSRS-PPP: Height Quality: GPS-alone Vs. GPS+GLONASS

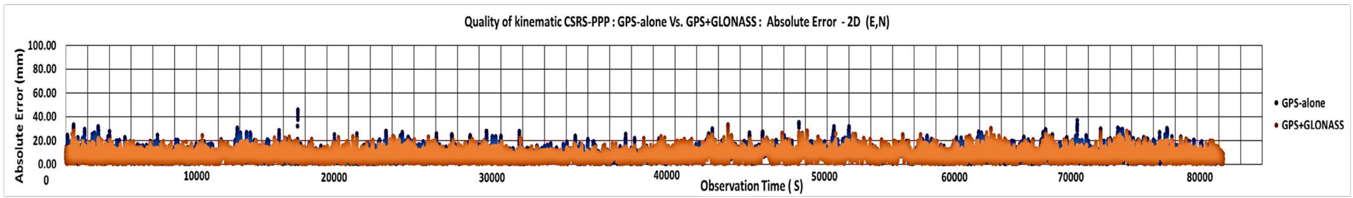

Fig. 6 CSRS-PPP: 2D (E&N) Quality: GPS-alone Vs. GPS+GLONASS

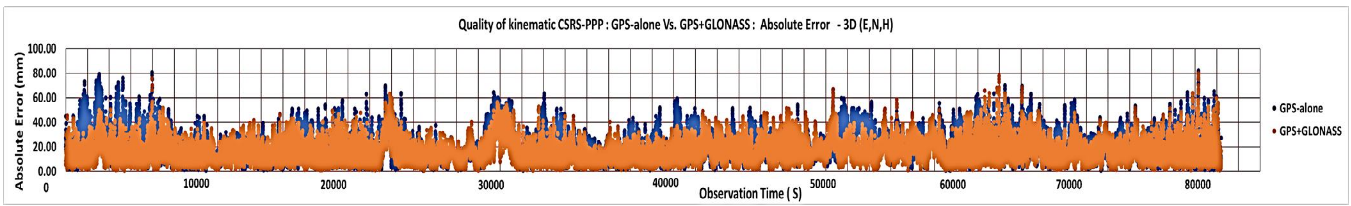

Fig. 7 CSRS-PPP: 3D (E,N,H) Quality: GPS-alone Vs. GPS+GLONASS

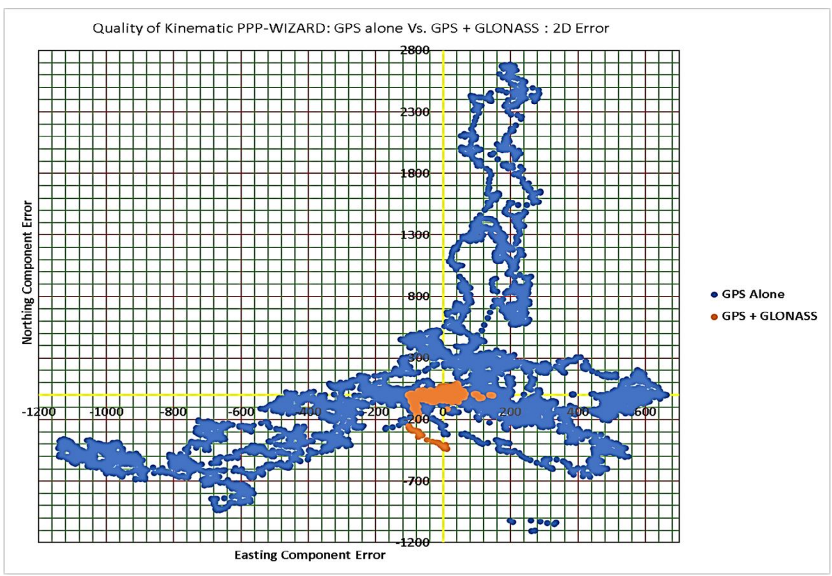

Fig. 8 PPP-WIZARD: 2D Quality: GPS-alone Vs. GPS+GLONASS [5]

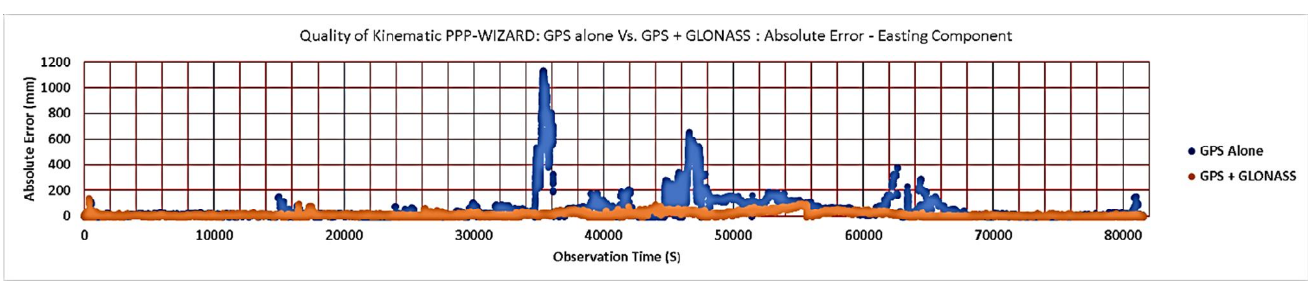

Fig. 9 PPP-WIZARD: Easting Quality: GPS-alone Vs. GPS+GLONASS [5]

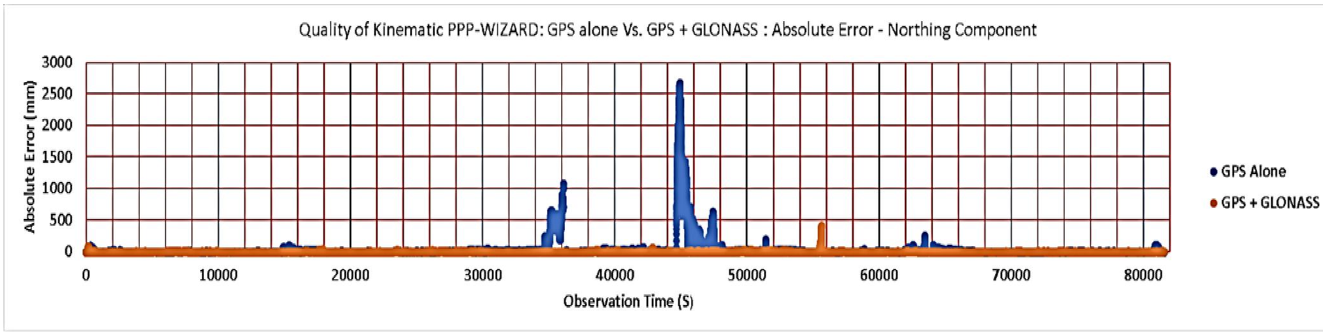

Fig. 10 PPP-WIZARD: Northing Quality: GPS-alone Vs. GPS+GLONASS [5]

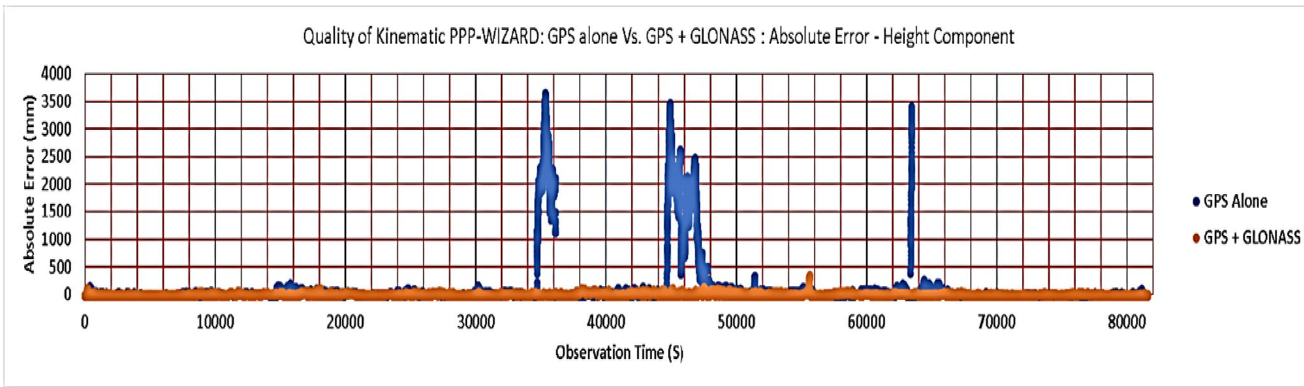

Fig. 11 PPP-WIZARD: Height Quality: GPS-alone Vs. GPS+GLONASS [5]

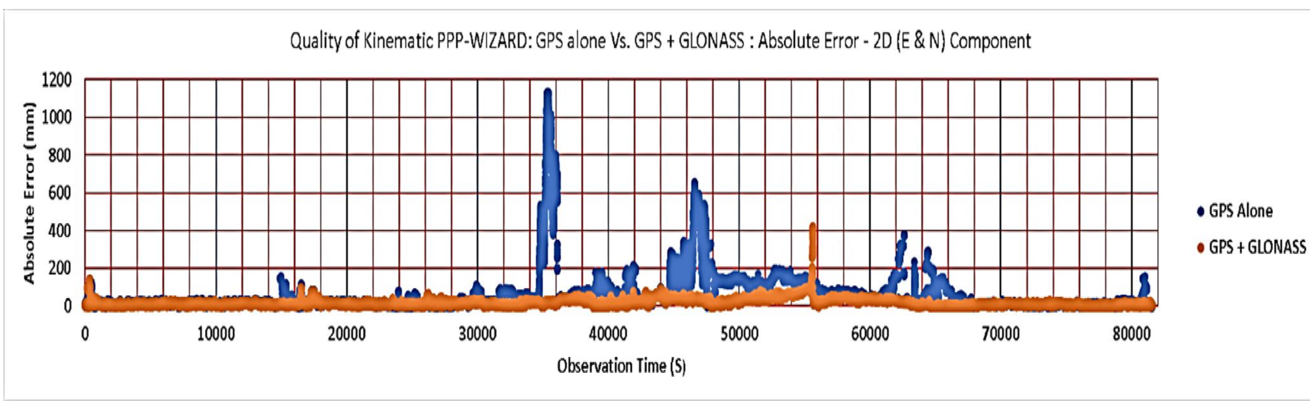

Fig. 12 PPP-WIZARD: 2D (E & N) Quality: GPS-alone Vs. GPS+GLONASS [5]

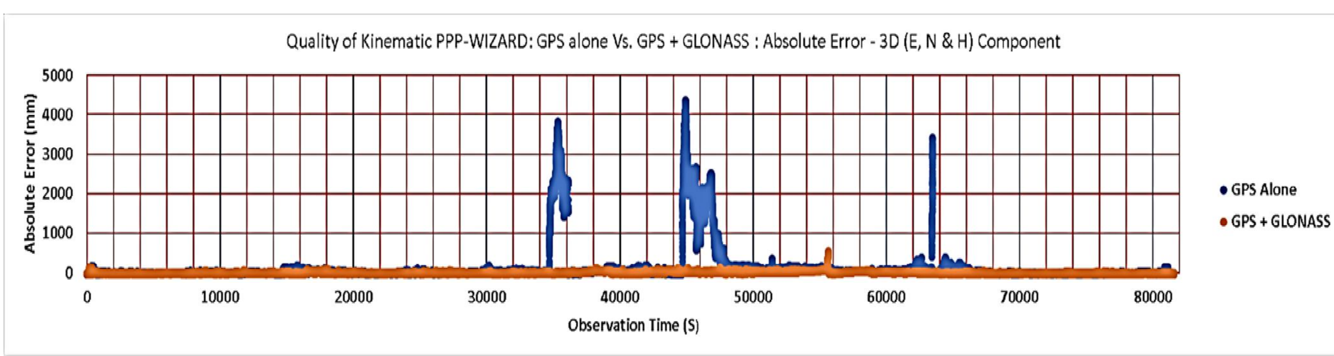

Fig. 13 PPP-WIZARD: 3D (E, N & H) Quality: GPS-alone Vs. GPS+GLONASS [5]

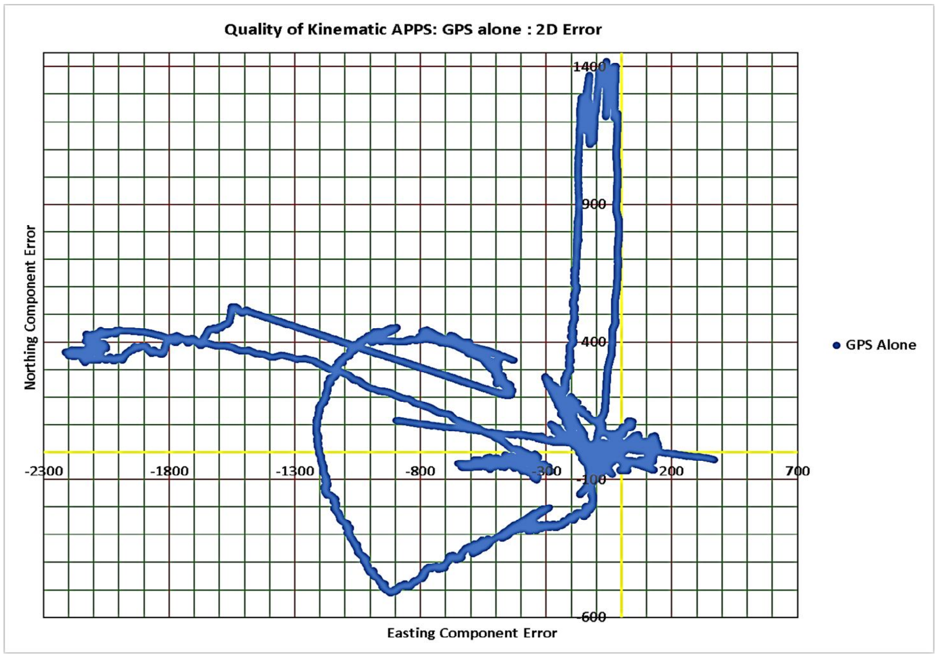

Fig. 14 APPS: 2D Quality of GPS-alone APPS kinematic solution [12]

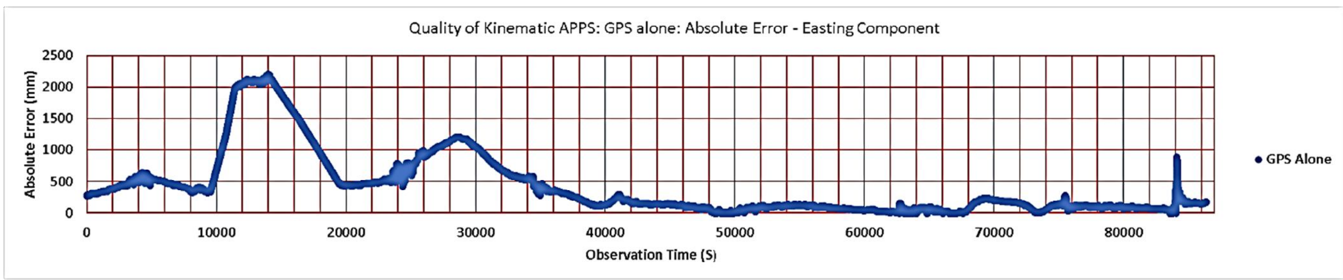

Fig. 15 APPS: Easting Quality of GPS-alone APPS kinematic solution [12]

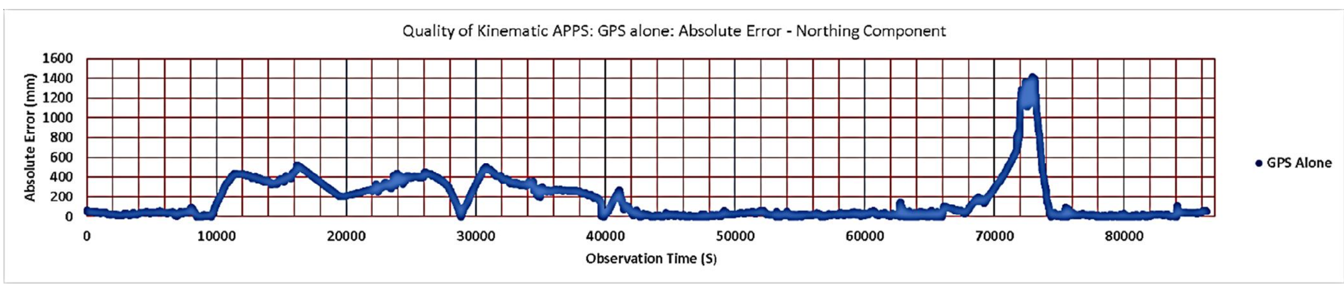

Fig. 16 APPS: Northing Quality of GPS-alone APPS kinematic solution [12]

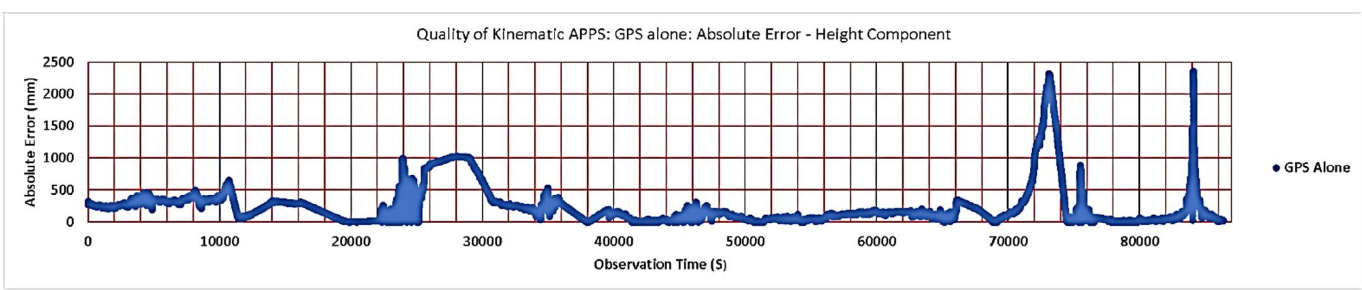

Fig. 17 APPS: Northing Quality of GPS-alone APPS kinematic solution [12]

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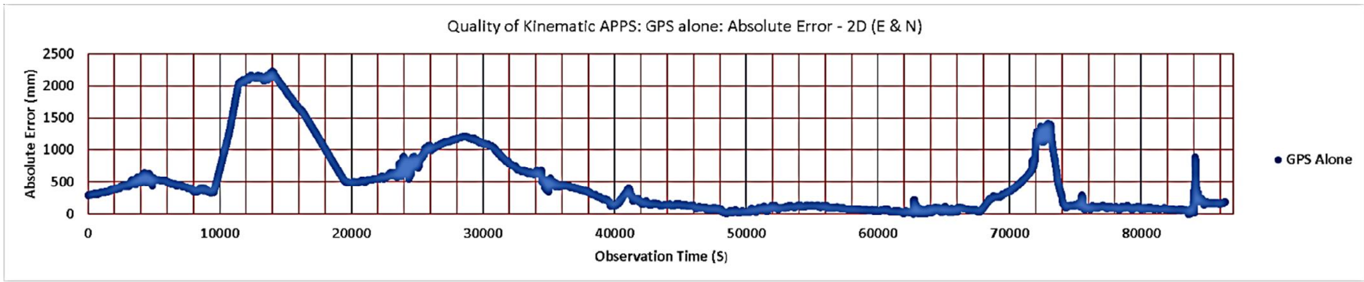

Fig. 18 APPS: 2D (E & N) Quality of GPS-alone APPS kinematic solution [12]

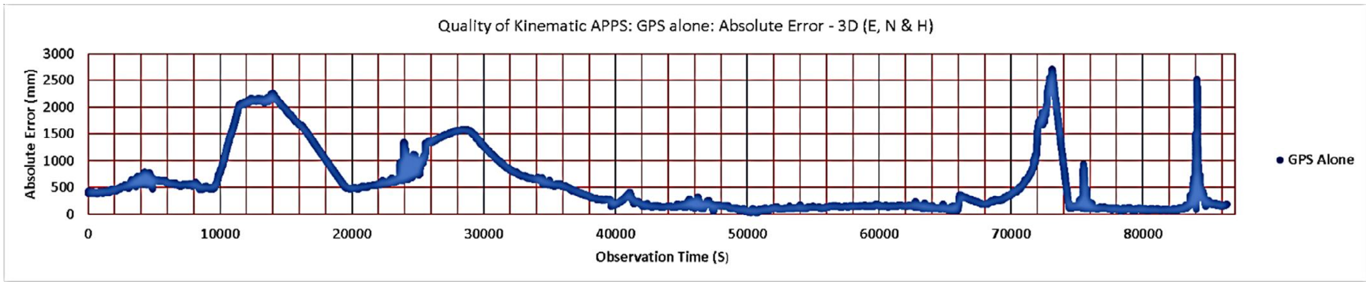

Fig. 19 APPS: 3D (E, N & H) Quality of GPS-alone APPS kinematic solution [12]

Beginning with CSRS-PPP, the results indicate that both processing configurations deliver highly accurate kinematic solutions at the centimeter level across all coordinate components. CSRS-PPP produces stable and continuous solutions with 0% outliers (defined as errors exceeding 5 cm in E and N, and 10 cm in H), AAE and RMSE values below 2 cm in all components, and three-dimensional MAE values of less than 10 cm and 7 cm for GPS-only and GPS+GLONASS solutions, respectively. A more detailed examination reveals that the inclusion of GLONASS observations slightly enhances the robustness of the GPS-only CSRS-PPP solution and improves the consistency and reliability of kinematic PPP by approximately 13% in E, 15% in N, and 21% in H. In addition, the maximum magnitude of gross errors is reduced when GLONASS observations are integrated, with reductions of approximately 1 cm in E and N, and 2 cm in H, as indicated in the corresponding results table.

For PPP-WIZARD, the results demonstrate that incorporating GLONASS observations leads to a substantial improvement in kinematic PPP performance compared to GPS-only processing. Specifically, RMSE values in the E, N, and H components decrease from approximately 11 cm, 17 cm, and 44 cm for GPS-only solutions to about 2 cm, 1.5 cm, and 2 cm when GPS and GLONASS observations are combined. Moreover, the multi-constellation approach significantly enhances positional precision by reducing the proportion of gross errors (greater than 5 cm in E and N, and 10 cm in H) from 33%, 8%, and 12% in GPS-only kinematic PPP solutions to 8%, 0.3%, and 0.35% in the E, N, and H components, respectively. Additional improvements are observed in MAE, which are reduced from 1.2 m, 2.6 m, and 3.2 m under GPS-only processing to 14 cm, 42 cm, and 37 cm when GLONASS observations are included. Compared to CSRS-PPP, the PPP-WIZARD kinematic solution using multi-constellation observations can be considered acceptable for certain engineering applications that require decimeter-level accuracy. However, the GPS-only PPP-WIZARD solution exhibits degraded and unreliable performance, with accuracy deteriorating to the meter level and a significant proportion of outliers.

In the case of APPS, the results indicate that the GPS-alone kinematic PPP solution provides continuous positioning solutions with AAE values of 0.42 m, 0.175 m, and 0.485 m, MAE of (2.2 m, 1.5 m, and 2.3 m), and RMSE values of 0.5 m, 0.21 m, and 0.31 m in E, N, and H components, respectively. The percentage of kinematic epoch solutions exceeding 5 cm in E and N and 10 cm in H is 64%, 38%, and 45% for the E, N, and H components, in that order. When compared with CSRS-PPP and PPP-WIZARD multi-constellation solutions, APPS yields unstable, imprecise, and unreliable results, resembling the performance of GPS-alone PPP-WIZARD in terms of AAE, but with a considerably higher proportion of outliers.

The performance improvements observed with multi-constellation processing can be primarily attributed to the increased number of tracked satellites and the resulting enhancement in satellite geometry, particularly during periods of limited GPS satellite availability. Improved geometry leads to lower dilution of precision (DOP) values, thereby strengthening the overall positioning solution. Furthermore, a well-distributed satellite configuration enables more reliable modeling of ionospheric and tropospheric delays, contributing to improved estimation of atmospheric effects.

Another important benefit of increased satellite availability is the higher degree of freedom in the observation equations, which facilitates the effective detection and exclusion of measurements with large residuals without compromising solution quality. In addition, the availability of a larger satellite set allows the exclusion of satellites observed at very low elevation angles, whose signals are typically noisier due to longer atmospheric propagation paths. By reducing the influence of such low-quality observations, the robustness and precision of kinematic PPP solutions are further enhanced. The degraded performance observed for APPS and GPS-only PPP-WIZARD may be attributed to the strong dependence of the employed PPP processing algorithms on a high degree of freedom in the observation equations to suppress outliers and achieve high-quality results. This reliance likely reflects the widespread adoption of multi-constellation GNSS processing, rendering single-constellation solutions increasingly uncommon. Moreover, such algorithms may rely on localized mathematical models for ionospheric and tropospheric delay estimation, which limits their effectiveness to local or regional applications.

IV. CONCLUSIONS

This study evaluated the performance of kinematic Precise Point Positioning (PPP) using three free online services, namely: the Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP), PPP-WIZARD, and the Automatic Precise Positioning Service (APPS). The evaluation was conducted under open-sky conditions to avoid multipath effects and under two processing configurations: GPS-alone and GPS+GLONASS. Dual-frequency GNSS observations were collected at 10 well-distributed reference points across Libya, with each site observed continuously for 24 hours and processed in kinematic mode. The performance assessment was based on four statistical indicators: Average Absolute Error (AAE), Maximum Absolute Error (MAE), Root Mean Square Error (RMSE), and the percentage of outliers exceeding 5 cm in the Easting (E) and Northing (N) components and 10 cm in the Height (H) component.

The results show that, in general, integrating GLONASS with GPS improves the quality of GPS-alone kinematic PPP solutions and significantly reduces the percentage of gross errors. This improvement was slight in case of CSRS-PPP and considerable with PPP-WIZARD. CSRS-PPP provides the best overall performance among the three services, achieving 0% outliers, AAE and RMSE values of less than 2 cm in all components, and 3D-MAE values of less than 10 cm and 7 cm for GPS-alone and GPS+GLONASS, respectively. PPP-WIZARD ranks second, where the combined solution reduces RMSE values in E, N, and H by approximately 9 cm, 15 cm, and 42 cm, respectively, and decreases the proportion of outliers by about 25%, 7.5%, and 11.5%, in the same order. In addition, AAE and MAE values of kinematic PPP-WIZARD decrease substantially in E, N, and H by approximately 1 m, 2.2 m, and 2.8 m, respectively, when using the integrated constellations. APPS supports GPS observations only and even when compared with GPS-alone results from CSRS-PPP and PPP-WIZARD, it exhibits the lowest accuracy and the highest percentage of outliers. APPS yields 3D-AAE, 3D-MAE, and 3D-RMSE values of approximately 0.65 m, 3.5 m, and 0.63 m, respectively, with outlier percentages of 64% in E, 38% in N, and 45% in H.

Overall, the results clearly highlight the significant advantages of multi-constellation GNSS processing over single-system solutions, particularly in terms of increased observation redundancy, improved satellite geometry, and enhanced capability to mitigate weak or unreliable observations. The comparative results confirm that CSRS-PPP provides the best performance using both GPS-alone and GPS+GLONASS with slight differences for the benefit of the second. PPP-WIZARD came second with acceptable performance under the integrated constellation processing which can be used for some engineering applications that require decimeter level of accuracy. However, GPS-alone PPP-WIZARD and APPS kinematic solutions remain unstable, less precise, and characterized by a high percentage of gross errors.

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