KINEMATIC PPP USING MIXED GPS/GLONASS SINGLE-FREQUENCY OBSERVATIONS

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ABSTRACT: Nowadays, Precise Point Positioning (PPP) is a very popular technique for Global Navigation Satellite System (GNSS) positioning. The advantage of PPP is its low cost as well as no distance limitation when compared with the differential technique. Single-frequency receivers have the advantage of cost effectiveness when compared with the expensive dual-frequency receivers, but the ionosphere error makes a difficulty to be completely mitigated. This research aims to assess the effect of using observations from both GPS and GLONASS constellations in comparison with GPS only for kinematic purposes using single-frequency observations. Six days of the year 2018 with single-frequency data for the Ethiopian IGS station named “ADIS” were processed epoch by epoch for 24 hours once with GPS-only observations and another with GPS/GLONASS observations. In addition to “ADIS” station, a kinematic track in the New Aswan City, Aswan, Egypt, has been observed using Leica GS15, geodetic type, dual-frequency, GPS/GLONASS GNSS receiver and single-frequency data have been processed. Net_Diff software was used for processing all the data. The results have been compared with a reference solution. Adding GLONASS satellites significantly improved the satellite number and Position Dilution Of Precision (PDOP) value and accordingly improved the accuracy of positioning. In the case of “ADIS” data, the 3D Root Mean Square Error (RMSE) ranged between 0.273 and 0.816 m for GPS only and improved to a range from 0.256 to 0.550 m for GPS/GLONASS for the 6 processed days. An average improvement ratio of 24%, 29%, 30%, and 29% in the east, north, height, and 3D position components, respectively, was achieved. For the kinematic trajectory, the 3D position RMSE improved from 0.733 m for GPS only to 0.638 m for GPS/GLONASS. The improvement ratios were 7%, 5%, 28%, and 13% in the east, north, height, and 3D position components, respectively, for the kinematic trajectory data. This opens the way to add observations from the other two constellations (Galileo and BeiDou) for more accuracy in future research.

Keywords: Precise Point Positioning, GPS, GLONASS, Kinematic.

1. INTRODUCTION

Precise Point Positioning (PPP) is a positioning technique appeared in the past two decades; this new technique requires only one global navigation satellite system (GNSS) receiver, which makes it a cost effectiveness method when compared with the differential positioning technique. In the PPP technique, the processing procedure does not use the clock and satellite

ephemerides broadcasted in the navigation message. Instead of this, precise ephemerides and clock data are used. Those data are provided by specific organizations such as International GNSS Service (IGS, 2019).

PPP has several serious disadvantages; the most significant shortage is the long convergence time that may exceed 20 min to solve the ambiguity resolution in order to ensure centimeter-level positioning accuracy for dual-frequency observations and exceeds 30 min to ensure half meter level for single-frequency observations. Because of this shortage, the use of PPP in real-time applications has been limited. In addition to the convergence time, ionospheric delay makes a severe difficulty in single-frequency receivers for decimeter-level accuracy (Rizos et al., 2012).

For dual-frequency observations, it has been demonstrated that millimeter-level accuracy can be obtained using PPP in static mode. In kinematic mode, the centimeter-level accuracy can potentially be achieved (Gao and Chen, 2004; Choy, 2009; Li et al., 2011; Rizos et al., 2012).

Cai et al. (2013) proposed a combined GPS/GLONASS single-frequency PPP approach to improve the performance of GPS-only PPP using G_Roup And P_Hase Ionospheric Correction (GRAPHIC) to remove the ionospheric effect. They performed a static and a kinematic tests. For the kinematic test, the RMSE for east, north, and height components was improved from 0.551, 0.188, and 0.511 m, respectively, in the case of GPS only to 0.322, 0.096, and 0.342 m, respectively, in the case of GPS/GLONASS.

El Manaily et al. (2017) investigated the performance of Quad-GNSS static positioning for dual- and single-frequency observations in Egypt. Data collected in 2 consecutive days at three different stations over Egypt have been processed. They used GRAPHIC combination to remove ionospheric delay. For single-frequency data, the achieved 3D position accuracy after 5 min was 3.590 m and improved to 0.280 m after 240 min in the case of GPS only. For the GPS/GLONASS case, it was 2.800 m after 5 min and improved to 0.230 m after 240 min. The best results were achieved using the four constellations with a 3D position error of 2.720 m after 5 min and 0.220 m after 240 min.

Pan et al. (2017) presented a Four-constellation Single Frequency Precise Point Positioning (FCSF-PPP) model based on GRAPHIC combination to remove the ionospheric effect. Data sets from 47 globally distributed four-system Multi-GNSS EXperimental (MGEX) stations with observations from GPS, GLONASS, BeiDou, and Galileo constellations as well as a kinematic experiment data set were used to fully assess the performance of FCSF-PPP. The accuracy in terms of RMSE was computed from the positioning errors in the last hour. For the static data set, the 3D positioning accuracy after 12 h was 0.420, 0.031, and 0.022 m for GPS only, GPS/GLONASS, and Quad-constellation, respectively. For the kinematic data set, the achieved accuracy for GPS-only case was 0.186, 0.137, and 0.332 m in the east, north, and height components, respectively. For GPS/GLONASS case, the accuracy improved to 0.130, 0.109, and 0.239 m in the three directions. The FCSF-PPP improved the accuracy to 0.116, 0.780, and 0.209 m in the east, north, and up directions, respectively. In comparison with GPS-only and GPS/GLONASS cases, the FCSF-PPP showed a better performance in terms of accuracy and convergence time.

Farah (2018) conducted an evaluation study for the dual- and single-frequency kinematic PPP precision for hydrography using different constellations. The Canadian Spatial Reference System (CSRS-PPP) online service had been used to perform all the processing scenarios. Using GPS-only constellation, the average accuracy attained using single-frequency observations was 3.00 and 8.30 m for horizontal and vertical components, respectively. Using

GPS/GLONASS constellations, the average accuracy was 2.70 and 7.30 m for horizontal and vertical components, respectively. The combined solution improved the kinematic PPP precision by about 11% over the GPS-only solution.

2. MATHEMATICAL MODEL

The GPS/GLONASS observation equations for static and kinematic PPP can be represented by the following equations (Cai and Gao, 2007):

$$P_{Li}^g = \rho^g + C(dt^g - dT^g) + d_{orb}^g + d_{trop}^g + d_{ion}^g + d_{mult/P_{Li}}^g + \varepsilon_{P_{Li}}^g \quad (1)$$

$$\varphi_{Li}^g = \rho^g + C(dt^g - dT^g) + d_{orb}^g + d_{trop}^g - d_{ion}^g + \lambda_{Li}^g N_{Li}^g + d_{mult/\varphi_{Li}}^g + \varepsilon_{\varphi_{Li}}^g \quad (2)$$

$$P_{Gi}^r = \rho^r + C(dt^r - dT^r) + d_{orb}^r + d_{trop}^r + d_{ion}^r + d_{mult/P_{Gi}}^r + \varepsilon_{P_{Gi}}^r \quad (3)$$

$$\varphi_{Gi}^r = \rho^r + C(dt^r - dT^r) + d_{orb}^r + d_{trop}^r - d_{ion}^r + \lambda_{Gi}^r N_{Gi}^r + d_{mult/\varphi_{Gi}}^r + \varepsilon_{\varphi_{Gi}}^r \quad (4)$$

where

The superscripts g and r refer to GPS and GLONASS, respectively,

The subscripts L and G refer to the GPS L1 and L2 and GLONASS G1 and G2 frequencies, respectively.

P_i	is the measured pseudorange (m)	d_{trop}	is the tropospheric delay (m)
φ_i	is the measured carrier phase (m)	d_{ion}	is the ionospheric delay (m)
ρ	is the geometric range (m)	λ	is the wavelength (m/cycle)
c	is the speed of light (m/s)	N	is the integer ambiguity number (cycle)
dt	is the receiver clock error (s)	$d_{mult/P_{Li}}$	is the multipath effect in the measured pseudorange (m)
dT	is the satellite clock error (s)	$d_{mult/\varphi_{Li}}$	is the multipath effect in the measured carrier phase (m)
d_{orb}	is the satellite orbit error (m)	ε	is the measurement noise (m)

3. METHODOLOGY OF PPP COMPUTATION OF GPS/GLONASS OBSERVATIONS

Fig. 1. The proposed methodology

Figure 1 shows the proposed methodology used in this research. Single-frequency data for 6 consecutive days of “ADIS” IGS station in addition to a kinematic trajectory have been processed using PPP technique by Net_Diff software. Net_Diff is a software for GNSS download, positioning, and analysis. It supports the functions of Single Point Positioning (SPP)/PPP/Precise Point Positioning Ambiguity Resolution (PPPAR)/differential positioning/Real Time Kinematic (RTK). It can also be applied in SPP/PPP with BeiDou augmentation information. It supports data analysis, including coordinate plotting, satellite number, PDOP, satellite sky view, positioning residuals, and so on. It provides IGS data and products download. It also provides some useful tools such as time and coordinate system transfer and RINEX edit (Yize, 2018; GitHub, 2019).

A differential solution has been performed for the kinematic track data using Leica Geo Office software version 7.0. (Leica Geosystems, 2019). The differential results were calibrated by comparing two lengths: the first length is an observed one and the second is fixed as a side of a steel bar used as a base for the GNSS receiver. Reference coordinates provided by CODE have been used to compare the results of “ADIS” station data (CODE, 2019).

Final Global Ionosphere Maps (GIM) provided by IGS have been used for mitigating the ionospheric error and Saastamoinen model with global mapping function for troposphere correction. The Kalman filter estimation has been applied. Table 1 presents the processing parameters used in Net_Diff software.

Table 1. PPP processing parameters used in Net_Diff software.

Reference system	ITRF2008
Coordinate format	LLH / XYZ / ENH (UTM)
Satellite orbit and clock ephemeris source	CODE final
Satellite phase center offset	IGS ANTEX
Receiver phase center offset	IGS ANTEX
Tropospheric model	Saastamoinen
Meteorological model	GPT
Mapping function	Global Mapping Function (GMF)
Ionospheric model	Final Global Ionospheric Maps (GIM) from IGS
Mask angle	10°
Observation type	Code + Phase
Frequency	L1
Processing mode	Kinematic
Estimation method	Kalman Filter

4. FIELD DATA

Two data sets have been processed in the test. The first data set is the observations for 6 consecutive days in the year 2018 with a 30 s recording interval for “ADIS” IGS station (at latitude 09°02′ N, longitude 38°46′ E). Those days are 20096, 20100, 20102, 20103, 20104, and 20105 in GPS date. The second data set is the kinematic trajectory observed on Tuesday, July 17, 2018 (GPS Date “20102”) with a length of 34 km in New Aswan City, Aswan, Egypt (at latitude 24°11′ N, longitude 32°51′ E) for 3 hours with a recording interval of 1 s and elevation angle of 10°. Dual-frequency Leica Viva GPS/GLONASS receiver was used for observing the trajectory (Leica GS15/GS10, 2012). In order to validate the PPP results, a differential solution has been implemented. The coordinates of the base point were derived from processing a static observation using the CSRS online service (CSRS-PPP, 2019). Figure 2 shows the kinematic trajectory with the position of the base station.

Fig. 2. The observed trajectory: New Aswan City, Aswan.

The base station is a local point over a building. Figure 3 shows the base station with the observing GPS/GLONASS Topcon Hiper GD dual-frequency receiver (Topcon Hiper GD and GGD, 2004) .

Fig. 3. The base station.

Fig. 4. The steel base with the two GNSS receivers.

The rover was fixed on a steel base over a moving vehicle with a constant speed of 20 km/h. Some parts of the trajectory were in open areas with a clear sky view and some were between buildings to let cycle slips happen and get a real life situation for the sky view. At a distance of 95 cm over the steel base, another dual-frequency Topcon Hiper GD rover was fixed. In order to calibrate the differential solution, the distance between the two rovers was calculated from the coordinates attained from the differential solution and compared with the fixed distance of 95 cm. Figure 4 shows the steel base with the two rovers Leica Viva GS15 and Topcon Hiper GD.

5. RESULTS

By processing the observation data for 6 consecutive days for “ADIS” IGS station as well as the kinematic trajectory using Net_Diff software with final products from IGS for GPS-only and GPS/GLONASS observations, it has been demonstrated that adding GLONASS satellites significantly improves the accuracy of the kinematic PPP solution.

5.1 For “ADIS” station data

Figures 5–16 show the variation of the satellite number and PDOP values over time for GPS-only and GPS/GLONASS cases for the 6 days. It is clear that the satellite number and PDOP have been enhanced significantly by adding the GLONASS satellites. For the GPS-only case, the satellite number decreased from 8 to 7 at epoch No. 687; consequently, the PDOP value jumped from 3.150 to 5.650. This jump is very clear in the PDOP chart for the 6 days represented in the peak of the blue-colored curve. After adding GLONASS satellites, the total satellite number increased to 14 at the same epoch so the PDOP value has been decreased to 1.500; it can be seen clearly by the orange-colored curve. Similarly, a decrease in the satellite number and an increase in the PDOP occurred at epochs 1017, 1670, and 2103 and the PDOP decreased after adding GLONASS satellites.

Fig. 5. Visible satellite number for GPS day 20096 for GPS only and GPS/GLONASS cases.

Fig. 6. Visible satellite number for GPS day 20100 for GPS only and GPS/GLONASS cases.

Fig. 7. Visible satellite number for GPS day 20102 for GPS only and GPS/GLONASS cases.

Fig. 8. PDOP values for GPS day 20096 for GPS-only and GPS/GLONASS cases.

Fig. 9. PDOP values for GPS day 20100 for GPS-only and GPS/GLONASS cases.

Fig. 10. PDOP values for GPS day 20102 for GPS-only and GPS/GLONASS cases.

Fig. 11. Visible satellite number for GPS day 20103 for GPS-only and GPS/GLONASS cases.

Fig. 12. Visible satellite number for GPS day 20104 for GPS-only and GPS/GLONASS cases.

Fig. 13. Visible satellite number for GPS day 20105 for GPS-only and GPS/GLONASS cases.

Fig. 14. PDOP values for GPS day 20103 for GPS-only and GPS/GLONASS cases.

Fig. 15. PDOP values for GPS day 20104 for GPS-only and GPS/GLONASS cases.

Fig. 16. PDOP values for GPS day 20105 for GPS-only and GPS/GLONASS cases.

Table 2 presents the average values of satellite number and PDOP for GPS-only and GPS/GLONASS cases. A significant improvement occurred after adding GLONASS satellites as indicated in the table. The average satellite number remained constant for the 6 days for both GPS-only and GPS/GLONASS cases. The average PDOP value changed slightly from one day to another for the both cases. For the 6 days, the average satellite number improved by about 67% and the average PDOP value improved by about 25% after adding GLONASS satellites.

Table 2. Average satellite number and PDOP values for GPS-only and GPS/GLONASS cases for 6 consecutive days and the improvement ratio.

GPS day		GPS only	GPS/GLONASS	Improvement ratio (%)
20096	Average satellite number	9	15	67
	Average PDOP	1.880	1.429	24
20100	Average satellite number	9	15	67
	Average PDOP	1.885	1.410	25
20102	Average satellite number	9	15	67
	Average PDOP	1.883	1.411	25
20103	Average satellite number	9	15	67
	Average PDOP	1.882	1.390	26
20104	Average satellite number	9	15	67
	Average PDOP	1.887	1.412	25
20105	Average satellite number	9	15	67
	Average PDOP	1.893	1.419	25

Figures 17–22 show the epoch-by-epoch error from the reference coordinates for GPS-only and GPS/GLONASS cases for the east component for the 6 days. The hobs in Figures 17, 19, and 20 are due to the elimination of the original ambiguity due to undetected cycle slip because of single-frequency data. It can be noticed that the values of the hobs became smaller in the case of GPS/GLONASS and the solution reconverged faster than GPS-only case.

Fig. 17. Difference between PPP solution and reference coordinates for the east component for GPS-only and GPS/GLONASS cases for GPS day 20096.

Fig. 18. Difference between PPP solution and reference coordinates for the east component for GPS-only and GPS/GLONASS cases for GPS day 20100.

Fig. 19. Difference between PPP solution and reference coordinates for the east component for GPS-only and GPS/GLONASS cases for GPS day 20102.

Fig. 20. Difference between PPP solution and reference coordinates for the east component for GPS-only and GPS/GLONASS cases for GPS day 20103.

Fig. 21. Difference between PPP solution and reference coordinates for the east component for GPS-only and GPS/GLONASS cases for GPS day 20104.

Fig. 22. Difference between PPP solution and reference coordinates for the east component for GPS-only and GPS/GLONASS cases for GPS day 20105.

Figures 23–28 show the epoch-by-epoch error from the reference coordinates for GPS-only and GPS/GLONASS cases for the north component for the 6 days.

The sudden hobs in the curves in Figures 25 and 26 are due to the wrong outlier detection by the software. This is caused by the undetected cycle slip or multipath error. After adding GLONASS satellites, it is clear that the size of the hobs decreased and some of them completely disappeared similar to that in Figure 27.

Fig. 23. Difference between PPP solution and reference coordinates for the north component for GPS-only and GPS/GLONASS cases for GPS day 20096.

Fig. 24. Difference between PPP solution and reference coordinates for the north component for GPS-only and GPS/GLONASS cases for GPS day 20100.

Fig. 25. Difference between PPP solution and reference coordinates for the north component for GPS-only and GPS/GLONASS cases for GPS day 20102.

Fig. 26. Difference between PPP solution and reference coordinates for the east component for GPS-only and GPS/GLONASS cases for GPS day 20103.

Fig. 27. Difference between PPP solution and reference coordinates for the east component for GPS-only and GPS/GLONASS cases for GPS day 20104.

Fig. 28. Difference between PPP solution and reference coordinates for the east component for GPS-only and GPS/GLONASS cases for GPS day 20105.

Figures 29–34 show the epoch-by-epoch difference between PPP and the reference coordinates for the height component for the 6 days.

Fig. 29. Difference between PPP solution and reference coordinates for the height component for GPS-only and GPS/GLONASS cases for GPS day 20096.

Fig. 30. Difference between PPP solution and reference coordinates for the height component for GPS-only and GPS/GLONASS cases for GPS day 20100.

Fig. 31. Difference between PPP solution and reference coordinates for the height component for GPS-only and GPS/GLONASS cases for GPS day 20102.

Fig. 32. Difference between PPP solution and reference coordinates for the height component for GPS-only and GPS/GLONASS cases for GPS day 20103.

Fig. 33. Difference between PPP solution and reference coordinates for the height component for GPS-only and GPS/GLONASS cases for GPS day 20104.

Fig. 34. Difference between PPP solution and reference coordinates for the height component for GPS-only and GPS/GLONASS cases for GPS day 20105.

Figures 35–40 shows the RMSE comparison between GPS-only and GPS/GLONASS cases for the 6 days. The RMSE values have been calculated after 1 h passed from the beginning of observation as a convergence time. From the figures, it is obvious that all the components of RMSE in the 6 days have been improved after adding GLONASS satellites into the processing. The largest RMSE was in the height component for GPS-only and GPS/GLONASS cases, and it had the largest improvement too. The RMSE in the north component had the smallest value for the majority of the days. It can also be noticed that whenever the component RMSE value is small, the improvement after adding GLONASS satellites is small too (in magnitude) and vice versa.

Fig. 35. RMSE comparison between GPS only and GPS/GLONASS for east, north, height, and position components for GPS day 20096.

Fig. 36. RMSE comparison between GPS only and GPS/GLONASS for east, north, height, and position components for GPS day 20100.

Fig. 37. RMSE comparison between GPS only and GPS/GLONASS for east, north, height, and position components for GPS day 20102.

Fig. 38. RMSE comparison between GPS only and GPS/GLONASS for east, north, height, and position components for GPS day 20103.

Fig. 39. RMSE comparison between GPS only and GPS/GLONASS for east, north, height, and position components for GPS day 20104.

Fig. 40. RMSE comparison between GPS only and GPS/GLONASS for east, north, height, and position components for GPS day 20105.

Table 3. RMSE values for east, north, height, and position components for GPS-only and GPS/GLONASS cases for 6 consecutive days with the improvement ratio.

GPS day	component	GPS only	GPS/GLONASS	Improvement ratio (%)
20096	East (m)	0.298	0.184	38
	North (m)	0.104	0.083	20
	Height (m)	0.591	0.384	35
	Position (m)	0.670	0.434	35
20100	East (m)	0.098	0.090	9
	North (m)	0.077	0.069	11
	Height (m)	0.243	0.230	5
	Position (m)	0.273	0.256	6
20102	East (m)	0.282	0.224	21
	North (m)	0.248	0.160	36
	Height (m)	0.724	0.476	34
	Position (m)	0.816	0.550	33
20103	East (m)	0.234	0.154	34
	North (m)	0.270	0.157	42
	Height (m)	0.646	0.405	37
	Position (m)	0.738	0.461	38
20104	East (m)	0.089	0.081	9
	North (m)	0.086	0.072	17
	Height (m)	0.401	0.290	28
	Position (m)	0.420	0.310	26
20105	East (m)	0.160	0.145	9
	North (m)	0.104	0.087	16
	Height (m)	0.364	0.298	18
	Position (m)	0.411	0.343	17

5.2 For the kinematic trajectory

Figures 41 and 42 show the variation of the satellite number and PDOP values over time for the kinematic trajectory. Both the satellite number and PDOP value enhanced obviously after adding GLONASS satellites. For the GPS-only case, the satellite number at the beginning of the observation period was 6 so the PDOP had a large value of more than 4. After adding GLONASS satellites, the satellite number was increased to 12 and the PDOP value was reduced significantly to about 2. At epoch No. 8133, the satellite number extremely decreased because of buildings so the PDOP value jumped to a maximum value of 16.360; at these epochs, adding GLONASS satellites did not improve the PDOP value, but in some, it became worst because of buildings blockage. The total average satellite number increased from 7 to 13 by a 85% improvement. Also, the PDOP value decreased from an average value of 2.185 to 1.517 by a 30% improvement.

Fig. 41. Visible satellite number values for the kinematic trajectory for GPS-only and GPS/GLONASS cases.

Fig. 42. PDOP values for the kinematic trajectory for GPS-only and GPS/GLONASS cases.

Figures 43–45 show the epoch-by-epoch error from the differential solution for GPS-only and GPS/GLONASS cases for east, north, and height components, respectively, for the kinematic trajectory. It can be seen that all the three components improved after adding GLONASS satellites. The hobs in the values are due to the same reason explained in “ADIS” data results section. As in “ADIS” data, the majority of the hobs have been reduced or disappeared after adding GLONASS satellites. By examining the curves at the beginning of observation time, it is clear that the height component took the shortest convergence, whereas the east component took the longest one.

Fig. 43. Epoch-by-epoch error from the differential solution for the kinematic track for GPS-only and GPS/GLONASS cases for the east component.

Fig. 44. Epoch-by-epoch error from the differential solution for the kinematic track for GPS-only and GPS/GLONASS cases for the north component.

Figure 46 shows a comparison of the RMSE in GPS-only and GPS/GLONASS cases. As shown in the figure, the north component has the largest RMSE, whereas the east component has the smallest one. This is because the north component took a longer convergence time.

Fig. 45. Epoch-by-epoch error from the differential solution for the kinematic track for GPS-only and GPS/GLONASS cases for the height component.

Fig. 46. A comparison of the RMSE for the kinematic track between GPS-only and GPS/GLONASS cases for the east, north, height, and 3D position components.

Table 4 presents the RMSE values for GPS-only and GPS/GLONASS cases with the improvement ratio after adding GLONASS satellites.

Table 4. RMSE values for the kinematic track for GPS-only and GPS/GLONASS cases for the east, north, height, and 3D position components with the improvement ratio.

Component	GPS	GPS/GLONASS	Improvement ratio (%)
RMSE E (m)	0.284	0.264	7
RMSE N (m)	0.511	0.484	5
RMSE H (m)	0.443	0.321	28
RMSE Position (m)	0.733	0.638	13

6. DISCUSSION

From the previous charts and tables, it is obvious that adding GLONASS satellites to the observations has a significant contribution to the improvement in the overall attained accuracy. For “ADIS” station data, the improvement in satellite number and PDOP values are almost the same in the 6 processed days. The satellite number increased after adding GLONASS satellites, and, consequently, the PDOP value has been decreased. The improvement in the PDOP value was very obvious at the epochs when the GPS satellite number decreased largely. This happened at epoch No. 687 in the 6 days, and the PDOP has been reduced from 5.650 to 1.500 after the satellite number increased from 7 to 14. The RMSE values in all components improved after adding GLONASS satellites and the improvement value increased whenever the RMSE error value is bigger. Hops in the RMSE values can be noticed on the curves; these hops are due to the elimination of the original ambiguity because of undetected cycle slip or multipath error. For the real kinematic trajectory data, similar results have been achieved. The satellite number and PDOP enhanced after adding GLONASS satellites especially at the beginning of the observation period. The RMSE values in the three components improved, and the biggest improvement was observed for the height component.

7. CONCLUSION

Single-frequency data for 6 consecutive days for “ADIS” IGS station as well as the kinematic trajectory that has been observed in the New Aswan City, Aswan, Egypt, have been processed using Net_Diff software in order to evaluate the effect of adding GLONASS satellites on the accuracy of PPP using single-frequency data. The results were compared with the reference coordinates from CODE for “ADIS” data and with the differential solution for the kinematic trajectory. For ADIS station data, the satellite number and PDOP value considerably enhanced after adding GLONASS satellites with an average ratio of 66.6% and 25%, respectively, for 6 days. The 3D position RMSE ranged between 0.273 and 0.816 m in the GPS-only case. The values decreased to a range from 0.256 to 0.550 m in the GPS/GLONASS case. The average RMSE for the 6 days improved by 20%, 23%, 26%, and 26% for the east, north, height, and 3D position components, respectively. For the kinematic trajectory, the average satellite number and PDOP value improved by a ratio of 85% and 30%, respectively.

The achieved RMSE was 0.284, 0.511, 0.443, and 0.733 m for the east, north, height, and 3D position components, respectively, in the case of GPS only. The values of RMSE improved to 0.264, 0.484, 0.321, and 0.638 m for the east, north, height, and 3D position components, respectively, after adding GLONASS satellites. The achieved improvement ratio was 7%, 5%, 28%, and 13% in the east, north, height, and 3D position components, respectively. The achieved results are very close to those achieved by Cai et al. (2013), especially in the east and height components. Also, the results are comparable with those achieved by Pan et al. (2017) taking into account the different circumstances of observations and the period taken for computing RMSE. The results are also comparable with those achieved by El Manaily et al. (2017), which are from static positioning. From these results, the profit and importance of using multi-constellation GNSS observations have been clarified, especially in urban areas. This provides an opportunity for using observations from the emerging satellite systems such as Galileo and BeiDou in the future for a better performance with a cost-effective method.

Acknowledgments

The authors are grateful to Mr. Yize Zhang for providing Net_Diff software and for his useful advices. The instruments used for collecting GNSS observations were provided by Surveying laboratory in Aswan Faculty of Engineering and Elmassa Consult office.

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Received: 2019-08-05,

Reviewed: 2019-10-17, by B. Oszczak, and 2019-10-17,

Accepted: 2019-12-02.