Static-PPP Performance using Multi-GNSS (Single, Dual and Triple) Frequency Observations

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Abstract: Precise Point Positioning (PPP) is relatively modern GNSS positioning technique that proved its efficiency comparing with traditional Differential positioning technique for more than three decades. PPP requires only one receiver collecting observations at unknown station, while Differential technique requires two receivers collecting observations simultaneously one at known-position station and the other at unknown station. Extensive mitigation of different GNSS errors is essential for PPP-collected observations. Static-PPP accuracy depends on different factors such as; used GNSS system; single (GPS(G) or GLONASS(R) or BeiDou(C) or Galileo(E)) or mixed-GNSS systems (GPS/GLONASS or GPS/GLONASS/BeiDou or GPS/GLONASS/BeiDou/Galileo), observations type (single or dual or triple frequency), satellites geometry and observations duration. This research investigates static-PPP accuracy variation on three different-latitude IGS stations based on different factors; used GNSS system (single or mixed), observations type (single or dual or triple frequency) and satellites geometry. It can be concluded that GRCE combination provides 3D-accuracy of (8 cm) using single frequency observations, (1.5 mm) using dual frequency observations and (1 mm) using triple frequency observations. GRCE combination provides a convergence time of only four minutes (8 epochs) for dual frequency observations.

Keywords: Multi-GNSS, Static-PPP, Single frequency, Dual frequency, Triple frequency

1. Introduction

GNSS users consider Differential Positioning the sole accurate positioning technique for many decades. Differential positioning provides the highest accuracy with many limitations. The limitations mainly encompasses; the need for a reference station (known coordinates), the distance limitation between the rover and reference station, and the need for simultaneous observations between the reference and rover stations. Differential positioning's limitations increase its cost over autonomous positioning (Hofmann-Wellenhof and Lichtenegger, 2008). Single Point Positioning (SPP) where observations are collected only at the unknown station, computes the unknown position without applying any corrections to errors faced by GNSS signals. SPP is not suitable for engineering applications because the accuracy is too bad. The need was essential for a cost-effective positioning technique that provides acceptable accuracy for many GNSS applications. Precise Point Positioning (PPP) technique met the requirements of this need (Chen and Gao, 2005; Leandro, 2009; Farah, 2013; Farah, 2014).

PPP is a cost-effective standalone positioning technique, requires a single GNSS receiver. PPP uses un-differenced, differenced single and dual frequency pseudorange and carrier-phase observations along with precise satellite orbit and clock products to produce decimeter to sub-centimeter positioning in real-time and post-processing (Bisnath and Gao, 2008; Cai, 2009; Soycan, 2012; Ding et al., 2018; Du et al., 2021).

Researches continue their effort during more than two decades to increase the accuracy provided by PPP. PPP accuracy depends mainly on used GNSS systems (single or mixed), observations type (single or dual or triple frequency), duration of observations, satellites geometry and processing software capabilities. PPP's achieved accuracy could benefit from advancement and modernization of satellite constellations. Since start of 2021, PPP users could depend on four different GNSS constellations; (GPS, GLONASS, BeiDou and Galileo). PPP accuracy could improve a lot by depending not only in one constellation but different mixed constellations such as (GPS/GLONASS or GPS/GLONASS/BeiDou or GPS/GLONASS/BeiDou/Galileo). Those different mixed constellations provide different types of observations (single or dual or triple) frequency observations. Capabilities of PPP- processing software affect resulted PPP-accuracy for different types of observations and different GNSS systems. Many online PPP-processing services are there for PPP users (CSRS-PPP, GAPS, APPS and magicGNSS) (Farah, 2016) and Net_Diff service (Net_Diff, 2021).

2. NET_DIFF Online PPP/RTK Service

Net_Diff (Github, 2021) is software for GNSS Download, Positioning and Analysis. It enables users to perform SPP/PPP/PPP-AR/DSPP/DPPP/RTK/PPP-RTK (Yize, 2018; Hamed et al., 2019). All the signals of the current GPS/GLONASS/BeiDou/Galileo/QZSS/IRNSS are supported from single-frequency to triple-frequency. It can also be applied in SPP/PPP with BeiDou augmentation information (authorized user). It supports data analysis, including coordinate plotting, coordinate comparison, satellite number, PDOP, satellite sky view, satellite visibility, cycle-slip, troposphere, ionosphere, observation minus correction, positioning residuals plotting and KML file writing. It provides GNS observation data and products download from many public FTP servers.

Net_Diff provides online PPP/RTK Service (Net_Diff, 2021). For GPS/GLONASS/BeiDou/ Galileo/QZSS, the single-frequency indicates L1/G1/B1/E1/L1; dual-frequency indicates L1L2/ G1G2/B1B3/E1E5a/L1L2; triple-frequency indicates L1L2L5/G1G2G3/B1B2B3/ E1E5aE5b/L1L2L5. Table 1 presents PPP processing parameters used in Net_Diff. software. The advantages of Net_Diff. service over other PPP-services is its ability to process observations from all available systems (GPS/GLONASS/BeiDou/Galileo/QZSS/IRNSS) with different combinations between those systems as well as its ability to process different-frequency observations (single/dual/triple). Those two advantages are ideal for research purposes.

Table 1. PPP processing parameters used in Net_Diff. service

Reference System	ITRF2008
Coordinate format	ENH (UTM)
Satellite orbit and clock ephemeris source	CODE final 30 sec. for clock 15 min for orbits
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	10º
Observation type	Code + Phase
System	GPS/GLONASS/BeiDou/Galileo/ QZSS/IRNSS
Frequency	Single/Dual/Triple
Processing mode	Static
Estimation method	Kalman Filter

3. Test Study Scope

The study investigates static-PPP accuracy under different parameters.

Table 2. Tested IGS stations' geographic coordinates (IGS, 2021).

IGS Station	Latitude (Deg. Min. Sec)	Longitude (Deg. Min. Sec)	Ellips. Height (m)
DGAR	S 07° 16' 10.86"	E 72° 22' 12.86"	-64.746
GAMG	N 35° 35' 24.25"	E 127° 55' 10.77"	927.965
MAR7	N 60° 35' 42.19"	E 17° 15' 30.38"	74.300

Those parameters are; used system (single or mixed), observation type (single or dual or triple) frequencies and satellite geometry. Single system includes (GPS or GLONASS or BeiDou or Galileo). Mixed systems include (GPS/GLONASS or GPS/GLONASS/BeiDou or GPS/GLONASS/BeiDou/ Galileo). Seven days during GPS week (2156) (2-8, May, 2021) were processed from three different-latitude IGS stations (IGS, 2021) (Table 2) with 30 sec. observation interval. The different processed observation files were extracted from stations' rinex files using TEQC software (TEQC, 2021). Table 3 presents average number of visible satellite, average PDOP and average GDOP for the tested three stations during the tested week

Table 3. Average (no. visible satellites, PDOP, GDOP) for tested IGS stations during GPS week (2156).

IGS Station	System	Average no. visible satellites	Average PDOP	Average GDOP
DGAR	G	9	1.811	2.035
	R	6	2.988	3.377
	C	11	2.037	2.435
	E	7	2.196	2.468
	GR	16	1.345	1.695
	GRC	27	1.002	1.445
	GRCE	35	0.876	1.402
GAMG	G	8	1.935	2.221
	R	6	2.895	3.332
	C	9	2.824	3.436
	E	6	2.461	2.841
	GR	15	1.392	1.808
	GRC	25	1.154	1.711
	GRCE	31	0.992	1.630
MAR7	G	9	1.870	2.112
	R	7	2.128	2.430
	C	4	9.629	11.160
	E	7	2.146	2.420
	GR	17	1.297	1.664
	GRC	21	1.145	1.637
	GRCE	29	0.977	1.559

4. Study Results

4.1 Single Frequency Static-PPP Positioning

3D-position error from true coordinates of Static-PPP precision for different single frequency observations from different; single systems (GPS(G), GLONASS(R), BeiDou(C) and Galileo(E)) and mixed systems (GPS/GLONASS (GR) GPS/GLONASS/BeiDou (GRC) and GPS/GLONASS/BeiDou/Galileo (GRCE)) starting from DOY 122 down to DOY 128 of GPS week 2156 resulting from this study are presented graphically (Figure 1) for the three tested IGS stations.

4.2 Dual Frequency Static-PPP Positioning

3D-position error of Static-PPP precision for different dual frequency observations from different; single and mixed systems (G, R, C, E, GR, GRC, GRCE) for DOY 122 down to DOY 128 of GPS week 2156 resulting from this study are presented in (Figure 2) for the three tested IGS stations.

4.3 Triple Frequency Static-PPP Positioning

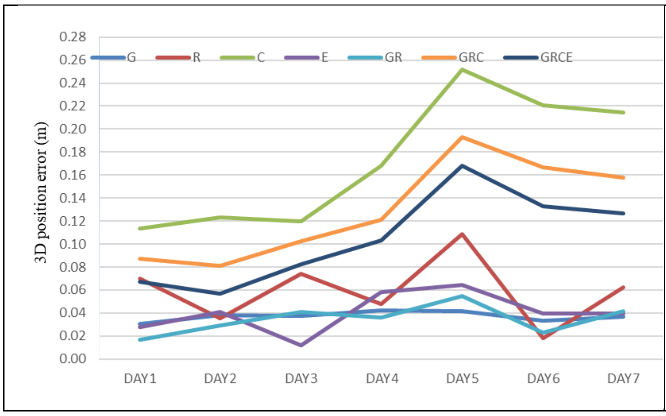
3D-position error of Static-PPP precision for different triple frequency observations from different; single and mixed systems (G, R, C, E, GR, GRC, GRCE) for DOY 122 down to DOY 128 of GPS week 2156 resulting from this study are presented (Figure 3) for the three tested IGS stations.

4.4 Convergence Time Effect

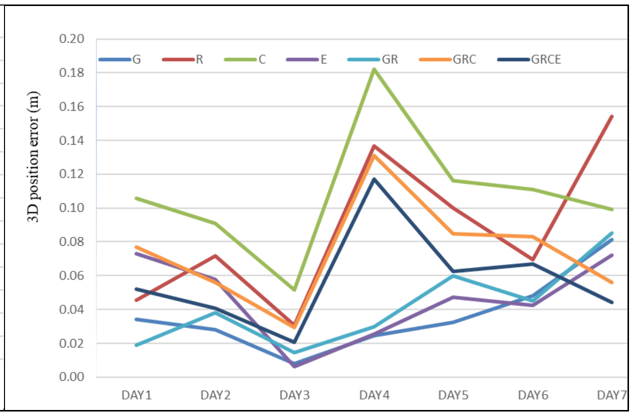
The convergence time of static-PPP solution is affected by number of used satellites and used observations which are dependent on used systems. More GNSS systems mean more observed satellites and more observations. To show the effect of using multi-GNSS on convergence time, the 3D accuracy difference from true coordinates was plotted (Figure 4) for station (DGAR) on (GPS day 21560) based on dual frequency observations solution. Table 4 presents 3D-Convergence time (10 cm-3D accuracy comparing with true coordinates) from Static-PPP solutions using dual-frequency observations from different systems for station (DGAR) for (GPS day 21560).

Table 4. 3D Convergence time (10 cm-3D accuracy comparing with true coordinates) from Static-PPP solutions using dual-frequency observations from different systems for station (DGAR) for (GPS day 21560).

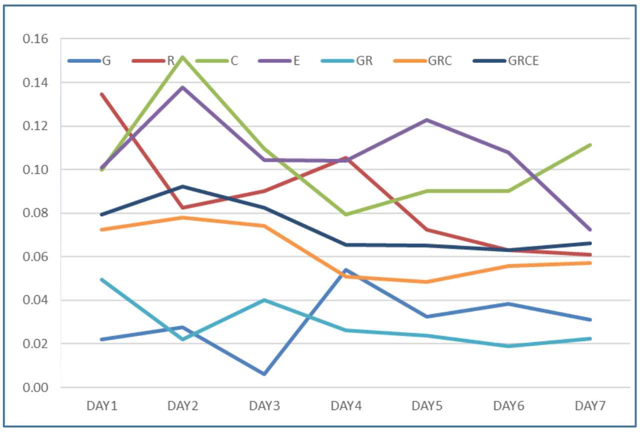
IGS Station	System	Convergence time (hh:mm:ss)
DGAR	G	00:15:30
	R	04:43:30
	C	00:12:30
	E	01:48:00
	GR	00:23:00
	GRC	00:07:30
	GRCE	00:04:00



a) **DGAR**

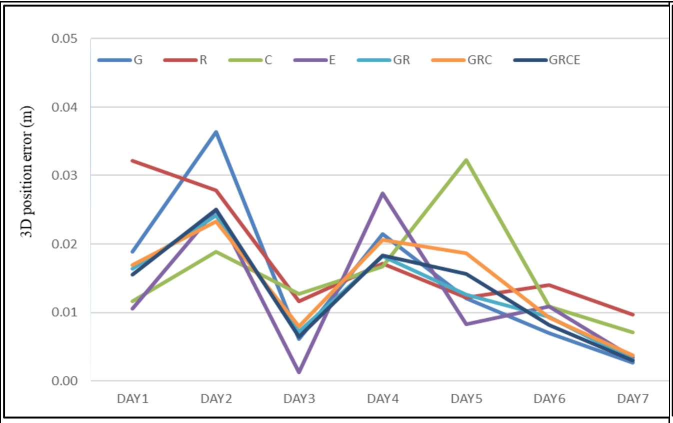


b) **GAMG**

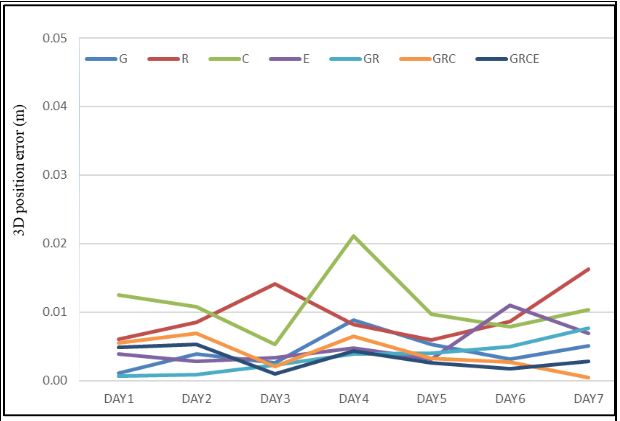


c) **MAR7**

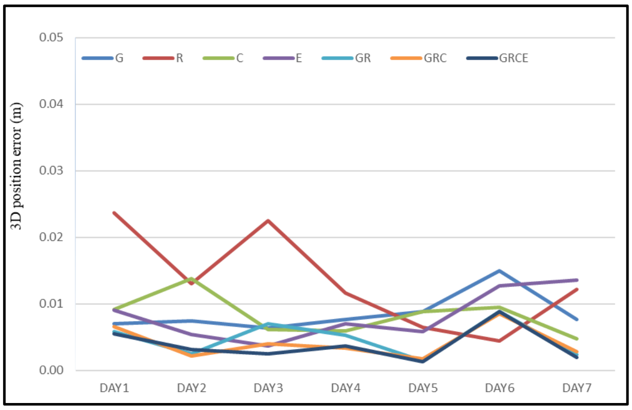
Figure 1. Static-PPP 3D-Position precision using single-frequency for GPS week (2156) of station



a) **DGAR**

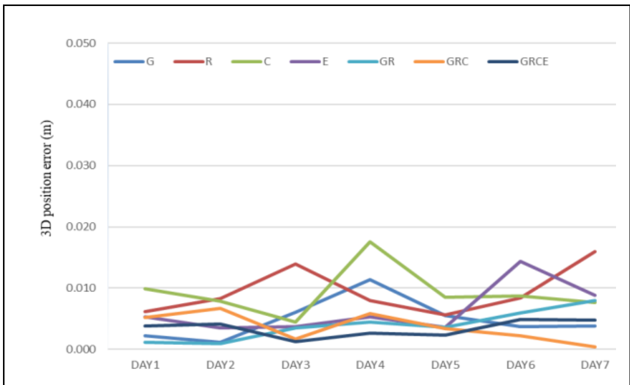


b) **GAMG**

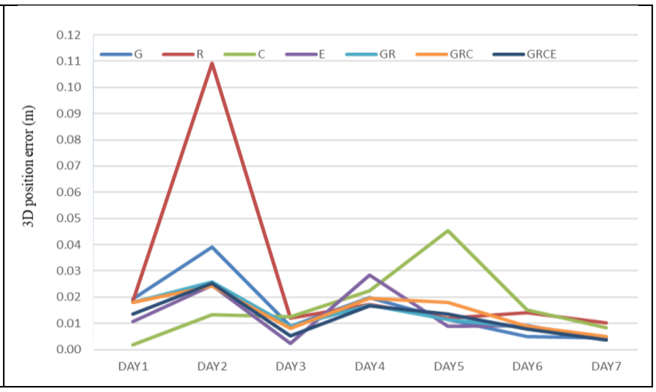


c) **MAR7**

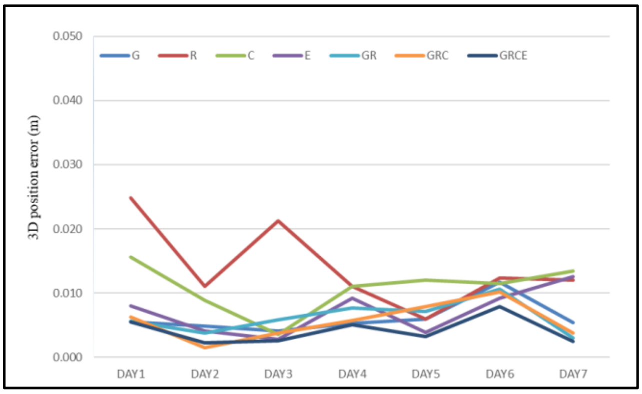
Figure 2. Static-PPP 3D-Position precision using dual-frequency for GPS week (2156) of station



a) **DGAR**



b) **GAMG**



c) **MAR7**

Figure 3. Static-PPP 3D-Position precision using triple-frequency for GPS week (2156) of station

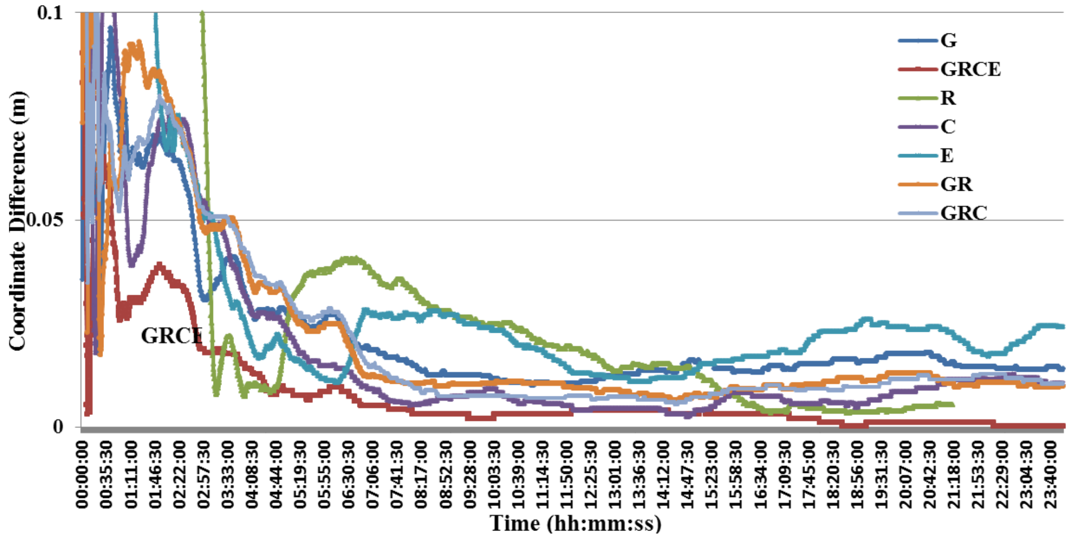


Figure 4. 3D coordinate difference from Static-PPP solution with true coordinates (meters) using dual-frequency observations from different systems for station (DGAR) for (GPS day 21560).

5. Discussion

This research presents a study for static-PPP performance under multi-GNSS systems using different types of observations (single & dual and triple) frequency. The study uses 7-days of observations for three different-latitude IGS stations. Tables 5, 6 and 7 present average Static-PPP accuracy 3D-differences from true coordinates for (GPS week 2156) for three tested stations using single frequency, dual frequency and triple frequency observations respectively.

Table 5. Average Static-PPP 3D-Position accuracy differences from true coordinates using single frequency Observations (GPS week 2156) for three tested stations.

IGS Station	System	3D-position error (m)
DGAR	G	0.019
	R	0.046
	C	0.172
	E	0.026
	GR	0.020
	GRC	0.129
	GRCE	0.105
GAMG	G	0.031
	R	0.084
	C	0.106
	E	0.039
	GR	0.040
	GRC	0.075
	GRCE	0.057
MAR7	G	0.027
	R	0.083
	C	0.101
	E	0.106
	GR	0.026
	GRC	0.061
	GRCE	0.073

Table 6. Average Static-PPP 3D-Position accuracy differences from true coordinates using dual frequency Observations (GPS week 2156) for three tested stations.

IGS Station	System	3D Position error (m)
DGAR	G	0.002
	R	0.006
	C	0.005
	E	0.007
	GR	0.001
	GRC	0.002
	GRCE	0.001
GAMG	G	0.002
	R	0.008
	C	0.010
	E	0.003
	GR	0.003
	GRC	0.004
	GRCE	0.002
MAR7	G	0.008
	R	0.012
	C	0.005
	E	0.006
	GR	0.002
	GRC	0.001
	GRCE	0.001

Table 7. Average Static-PPP 3D-Position accuracy differences from true coordinates using triple frequency Observations (GPS week 2156) for three tested stations.

IGS Station	System	3D Position error (m)
DGAR	G	0.005
	R	0.018
	C	0.011
	E	0.006
	GR	0.004
	GRC	0.002
	GRCE	0.000
GAMG	G	0.004
	R	0.008
	C	0.006
	E	0.004
	GR	0.004
	GRC	0.003
	GRCE	0.000
MAR7	G	0.006
	R	0.013
	C	0.006
	E	0.005
	GR	0.004
	GRC	0.003
	GRCE	0.000

Figure 1 present static-PPP precision variation using single frequency observations from different single and combined GNSS constellations during different days of GPS week 2156 for three different-latitude IGS stations. Table 5 presents average Static-PPP accuracy 3D-position differences from true coordinates using single frequency Observations (GPS week 2156) for three tested stations. From Table 3, it can be concluded that GPS provides the best PDOP comparing with other single systems for the three tested stations. GLONASS and Galileo provide similar consistent PDOP on average basis. BeiDou provides varying PDOP based on tested stations. GPS provides the best accuracy for static-PPP using single frequency observations comparing with other single systems. GR combination worsens the accuracy provided by GPS alone, while the attained accuracy is better than GLONASS alone. GRC combination provides better accuracy than GLONASS alone or BeiDou alone. Galileo alone provides better accuracies than GLONASS alone for the two mid-latitude stations (DGAR, GAMG). BeiDou alone provides the worst accuracy comparing with other single systems. Combining Beidou with other systems such as GRC or GRCE worsen the accuracy provided by GR. GPS provides average 3D-accuracy under or equal to 3 cm while GRCE provides 3D-accuracy under 10 cm. Those findings are constrained with this study's circumstances (visibility & PDOP). Varying circumstances could lead to different output accuracies from single and combined systems.

Figure 2 present static-PPP precision 3D-position variation using dual frequency observations from different single and combined GNSS constellations during different days of GPS week 2156 for three different-latitude IGS stations. Table 6 presents average Static-PPP 3D-accuracy differences from true coordinates using dual frequency Observations (GPS week 2156) for three tested stations. GPS provides the best accuracy for static-PPP using dual frequency observations comparing with other single systems for the two mid-latitude stations (DGAR, GAMG). GLONASS and BeiDou provide similar accuracies for the two mid-latitude stations. GR combination provides better accuracy than GPS alone or GLONASS alone. GRC combination provides better accuracy than any single system or GR combination. GRCE provides the best accuracy comparing with any single system or GR or GRC combinations. GRCE provides the 3D-accuracy of about 1mm.

Figure 3 present static-PPP precision 3D-position variation using triple frequency observations from different single and combined GNSS constellations during different days of GPS week 2156 for three different-latitude IGS stations. Table 7 presents average Static-PPP 3D-accuracy differences from true coordinates using triple frequency Observations (GPS week 2156) for three tested stations. Triple frequency observations provide similar performance to dual frequency observations. GPS provide the best accuracy comparing with any single system. Different combinations provide better accuracy than any single system. GRCE provides the best accuracy of less than 1 mm.

Figures 4 presents 3D coordinate difference from Static-PPP solution with true coordinates (meters) using dual-frequency observations from different systems for station (DGAR) for (GPS day 21560). Table 4 presents Convergence time (10 cm-3D accuracy comparing with true coordinates) from Static-PPP solutions using dual-frequency observations from different systems for station (DGAR) for (GPS day 21560). It can be concluded that GPS and BeiDou provide similar convergence time of about 15 minutes. GLONASS provide the longest convergence time of a single system with about 5 hours. Galileo provides a convergence time of about 2 hours. GR combination improves convergence time to 23 minutes. GRC combination improves the convergence time to about 8 minutes. GRCE combination gives the best convergence time of about 4 minutes (8 epochs of observations). Those attained convergence time depend on processing of 30 sec observation interval of the three tested IGS stations.

6. Conclusions

This research investigates static-PPP accuracy using different observations (single, dual and triple) from single system (G, R, C and E) and combined systems (GR, GRC and GRCE). It can be concluded that the attained accuracy directly depends on the used system constellation status which directly affects number of visible satellites and DOP values. Combined systems could improve satellite geometry and DOP values which remedy the deficiencies in one system and improve the attained accuracy from combined systems.

Under constraints of this study (tested stations & GPS week 2156) and the constellation status of tested systems, it can be concluded that GPS provides the best accuracy comparing with other single systems for different types of observations. Combining GPS with other systems could worsen the attained accuracy comparing with GPS-single system.

GRCE combination provides 3D-accuracy of (8 cm) using single frequency observations, (1.5 mm) using dual frequency observations and (1 mm) using triple frequency observations.

Static-PPP positioning using Combination of systems improves the convergence time remarkably. GRCE combination provides a convergence time of only four minutes (8 epochs) for dual frequency observations.

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