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Multi-Constellation GNSS Precise Point Positioning using GPS, GLONASS and BeiDou in Australia

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ABSTRACT

GNSS Precise Point Positioning (PPP) is a promising approach to high accuracy (centimetre to decimetre-level) positioning with a single receiver ,which does not need a nearby reference station like traditional precise positioning technique such as differential positioning. The advent of multi-constellation satellite systems, such as China’s BeiDou and European Union’s Galileo, offers additional satellites and observables, which can strengthen the positioning model thereby improving the accuracy and convergence time of PPP. This paper describes the prospects and challenges in combining multiple GNSS systems such as GPS+GLONASS+BeiDou in a PPP model. In particular, it aims to assess the performance of the combined system in terms of positional accuracy, reliability and time of convergence in static and kinematic PPP modes. The result indicates that the combined GPS+GLONASS+BeiDou kinematic PPP solution significantly improve the positioning accuracy by approximately 20% and 30% in the horizontal and vertical components, respectively; and also shorten the convergence time by more than 20% compared to GPS-only kinematic PPP solution. However, for the static PPP solution, the positioning accuracy and convergence time of the combined system is marginally improved compared to the GPS-only static PPP solution.

KEYWORDS: Precise Point Positioning (PPP), multi-constellation, GNSS, BeiDou, accuracy, convergence time

1. INTRODUCTION

Precise Point Positioning (PPP) technique using Global Positioning System (GPS) is a cost-effective high accuracy (centimetre to decimetre-level) positioning technique which has been widely used in many positioning and scientific applications in recent years (Zumberge et al.,1997; Defraigne et al., 2007; Kjorsvik et al., 2006; Larson et al., 2003; Leandro, 2009; Leandro et al., 2011; Li et al., 2013; Wright et al., 2012). However, the primary limitation of PPP is that it has long solution convergence time and also has low accuracy when the number of visible satellites is small in GNSS-challenged environment, such as urban canyons, open pits and mountains. Fortunately, several new global and regional navigation satellite systems (GNSS), such as the Chinese BeiDou satellite navigation system, Europe's Galileo, and the Japan's Quasi-Zenith Satellite System (QZSS) have emerged providing accurate position, navigation, and timing (PNT) service. Figure 1 shows the total number of satellites that were expected in 2010 from the various navigation satellite systems (Kogure, 2010). Multi-constellation systems can provide many advantages to stand-alone GPS navigation system(Montenbruck, 2014; Rizos, 2013). For example, new signals with higher power and better tracking performance, as well as increasing number of visible satellites could improve positioning in GNSS adverse environments .On the other hand, three frequencies positioning could provide new approaches to speed up ambiguity resolution process (e.g. Geng et al., 2010; Ge et al., 2008; Geng and Bock, 2013; Laurichesse et al., 2009) and eliminate higher-order ionosphere path delay. .

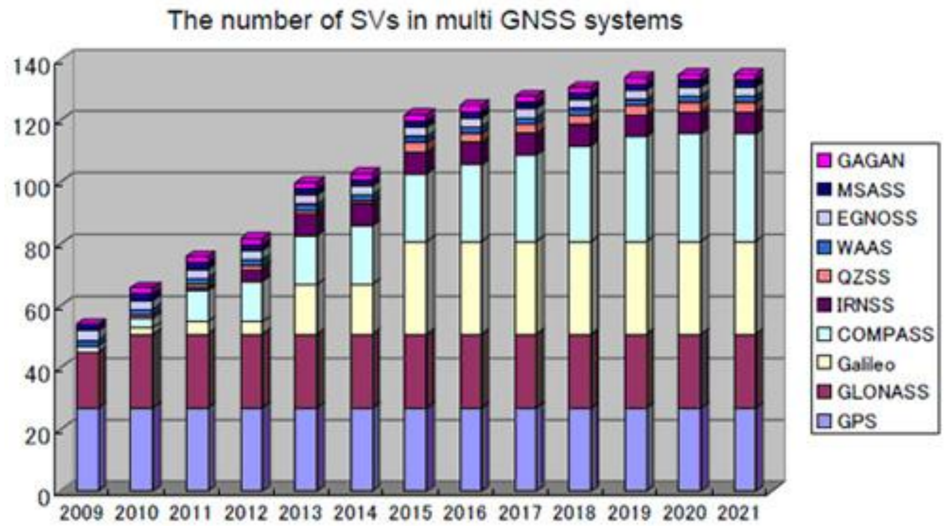


Figure 1. The number of SVs in multi GNSS systems (Kogure, 2010).

The International GNSS Service (IGS) has set up the Multi-GNSS Experiment (MGEX - http://igs.org/mgex) to promote the use of new emerging navigation satellite systems. The main objectives of the IGS MGEX are to establish a global multi-GNSS signals tracking network; to develop processing software capable of handling multiple GNSS observation data; and to provide high-quality data and products for all GNSS constellations (Montenbruck, 2014). Since the establishment of the IGS MGEX, more than 90 GNSS stations across the world has contributed offline and/or real-time data to the MGEX network (see Figure.2). In addition, there are five MGEX Analysis Centres providing different product types, e.g., precise satellite orbits, clocks and inter-system biases (see Table.1) making multi-GNSS PPP possible. Many researchers around the world have been investigating and evaluating the performance (accuracy and reliability) of multi-constellation PPP (Cai and Gao, 2013; Li and Zhang, 2014; Tegedor, 2014; Chen and Zhang, 2015; Li and Zhang et al., 2015).

In this paper, we present a study of multi-constellation GNSS PPP performance (GPS, GLONASS, BeiDou), both in static and kinematic mode, using GNSS observation data collected from three GNSS stations located in Melbourne, Australia. The accuracy, reliability and convergence time are also compared and analysed in GPS-only, GLONASS-only, BeiDou-only; and combined GPS+GLONASS, GPS+BeiDou, GLONASS+BeiDou, GPS+GLONASS+BeiDou. The final precise satellites clock and orbit products are obtained from the MGEX products website (IGS, 2015a).

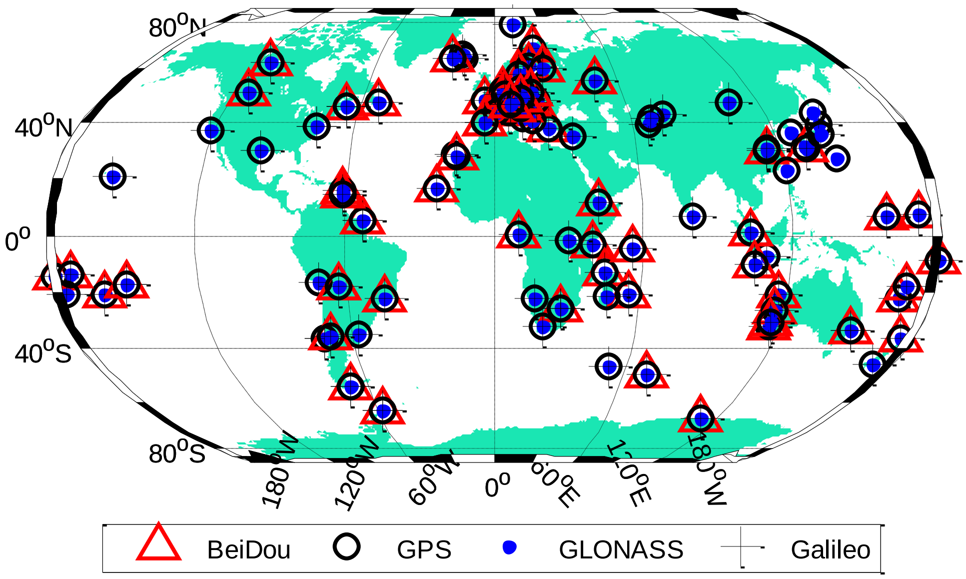


Figure 2. The IGS MGEX tracking stations network. Reference station tracking BeiDou are indicated as red triangle, GPS as hollow black circle, GLONASS as blue dot and Galileo as cross.

Table 1. The information of multi-GNSS precise orbit and clock products are provided from different MGEX analysis centres (IGS, 2015a).

Institution		**Products**	**Constellation**	**Availability (week/day)**
CNES/CLS	grmyyyyd.sp3	Orbits and Clocks (15 min)	GAL	Since 1692/1
CODE	comyyyyd.sp3 comyyyyd.clk	Orbits and Clocks (15 min) Clocks (5 min)	GPS+GLO+ GAL/GIO	Since 1689/5
GFZ	gfmyyyyd.sp3 gfmyyyyd.clk	Orbits (15 min) Clocks (5 min)	GPS+GAL	1680/0-1683/0
	gfbyyyyd.sp3 gfbyyyyd.clk	Orbits (15 min) Clocks (5 min)	GPS+BDS	Since 1777/2-1781/5
JAXA	qzfyyyyd.sp3	Orbits and Clocks (5min)	GPS+QZS	Since 1751/6
TUM	tumyyyyd.sp3	Orbits and Clocks (5min)	GAL+QZS	Since 1711/1
Wuhan Univ	wumyyyyd.sp3 wumyyyyd.clk	Orbits (15min) Clocks(5min)	BDS	since 1721/2

2. Multi-GNSS PPP Model

The basic observation equations of GNSS pesudorange and carrier phase observables (P_i and L_i ($i=1,2$)) between receiver "r" and satellite "j", could be written as:

$$\mathrm{P}_{r,i}^{j}=\rho_r^j+c\cdot(dt_r-dt^j)+d_{orb}^j+I_{r,i}^j+m_r^j\cdot ZTD+B_{r,i}-B_i^j+\varepsilon_{r,P_i}^j \tag{1}$$

$$L_{r,i}^{j}=\rho_r^j+c\cdot(dt_r-dt^j)+d_{orb}^j-I_{r,i}^j+m_r^j\cdot ZTD+N_{r,i}^j+b_{r,i}-b_i^j+\varepsilon_{r,L_i}^j \tag{2}$$

where ρ_r^j denotes the non-dispersive delay including the geometric distance, the phase center offsets and variations and station displacements by tidal loading, etc. (m); c is the speed of light in vacuum (m/s); dt_r and dt^j are the receiver "r" clock error and satellite "j" clock error (s), respectively; d_{orb}^j is the satellite orbit error (m); $I_{r,i}^j$ is the ionospheric delay of the signal path from receiver "r" to satellite "j" at at frequency i(m); m_r^j and ZTD are mapping function and zenith tropospheric delay, respectively; N_i is the integer phase ambiguity on L_i (m); $B_{r,i}$ and B_i^j are the receiver and satellite hardware code biases (m) on P_i, respectively; $b_{r,i}$ and b_i^j are the receiver and satellite phase biases on L_i (m); ε_{r,P_i}^j and ε_{r,L_i}^j are code and phase observation noises including the multipath (m), respectively.

To eliminate the ionosphere effects on satellite signals, we adopt the ionosphere-free linear combinations of code pseudorange and carrier phase observations. The observations equations could be written as:

$$\begin{aligned}P_{r,IF}^j&=\frac{f_1^2P_{r,1}^j}{f_1^2-f_2^2}-\frac{f_2^2P_{r,2}^j}{f_1^2-f_2^2}=c_1\cdot P_{r,1}^j+c_2\cdot P_{r,2}^j\\&=\rho_r^j+c\cdot(dt_r-dt^j)+d_{orb}^j+m_r^j\cdot ZTD+(c_1\cdot B_{r,1}+c_2\cdot B_{r,2})-(c_1\cdot B_1^j+c_2\cdot B_2^j)+\varepsilon_{r,P_{IF}}^j\\&=\rho_r^j+c\cdot(dt_r-dt^j)+d_{orb}^j+m_r^j\cdot ZTD+B_{r,IF}-B_{IF}^j+\varepsilon_{r,P_{IF}}^j\end{aligned} \tag{3}$$

$$\begin{aligned}L_{r,IF}^j&=\frac{\lambda_2^2L_{r,1}^j}{\lambda_2^2-\lambda_1^2}-\frac{\lambda_1^2L_{r,2}^j}{\lambda_2^2-\lambda_1^2}=c_1\cdot L_{r,1}^j+c_2\cdot L_{r,2}^j\\&=\rho_r^j+c\cdot(dt_r-dt^j)+d_{orb}^j+m_r^j\cdot ZTD+(c_1\cdot N_{r,1}^j+c_2\cdot N_{r,2}^j)+(c_1\cdot b_{r,1}+c_2\cdot b_{r,2})-(c_1\cdot b_1^j+c_2\cdot b_2^j)+\varepsilon_{r,L_{IF}}^j\\&=\rho_r^j+c\cdot(dt_r-dt^j)+d_{orb}^j+m_r^j\cdot ZTD+\mathrm{N}_{r,IF}^j+b_{r,IF}-b_{IF}^j+\varepsilon_{r,L_{IF}}^j\end{aligned} \tag{4}$$

where L_{IF} and P_{IF} are the ionosphere-free phase and code pseudorange observable in meters, respectively; $B_{r,IF}$ and B_{IF}^j are the receiver and satellite hardware code biases (m) on the ionosphere-free pseudorange combined P_{IF}; whereas $b_{r,IF}$ and b_{IF}^j denote those on L_{IF} (m); and N_{IF} represents the ionosphere-free linear combination of ambiguities.

The hydrostatic tropospheric zenith delay can be modelled using a tropospheric model with an accuracy level of 1.5-3mm (Niell, 1996). The non-hydrostatic (wet) delay component, on the other hand, is estimated as part of the parameter estimation (Heroux and Kouba, 2001). IGS precise ephemeris products include the ionosphere free satellite clock ($cd\overline{t}_{IF}^j=cdt^j+B_{IF}^j$) and precise satellite orbits. When corrected for these products, equations (3) and (4) becomes

$$P_{r,IF}^{j} + cd\overline{t}_{IF}^{j} = \overline{\rho}_{r}^{j} + cd\overline{t}_{r,IF} + m_{r}^{j} \cdot ZTD + \varepsilon_{r,P_{IF}}^{j} \tag{5}$$

$$L_{r,IF}^{j} + cd\overline{t}_{IF}^{j} = \overline{\rho}_{r}^{j} + cd\overline{t}_{r,IF} + m_{r}^{j} \cdot ZTD + \overline{\mathrm{N}}_{r,IF}^{j} + \varepsilon_{r,L_{IF}}^{j} \tag{6}$$

Where $cd\overline{t}_{r,IF} = cdt_{r} + B_{r,IF}$ is the iono-free receiver clock, orbit errors are considered insignificant when using IGS precise orbits, and

$$\overline{N}_{r,IF}^{j} = c_{1}N_{r,1}^{j} + c_{2}N_{r,2}^{j} + b_{r,IF} - b_{IF}^{j} + B_{IF}^{j} - B_{r,IF} \tag{7}$$

is the "float ambiguity" which is estimated as an additional parameter.

It is worth noting that different satellite navigation systems refer to different reference time, and the receiver clock error is the offset related to a single common reference time. When using the IGS clock products, the clocks are referenced to GPS time hence the receiver clock errors are estimated with reference to GPS time. The Inter-System Bias (ISB) between different satellite systems (GPS/GLONASS/BeiDou) must be taken into consideration when processing multi-GNSS observations. Apart from the ISB parameters, the Inter-Frequency Bias (IFB) needs to be considered as the GLONASS system uses Frequency Division Multiple Access (FDMA) signal scheme, which result in receiver- and satellite-biases that are frequency dependent. If GPS time is used as the reference time, Equations (5) and (6) can be expanded to multi-constellation PPP observations model for GPS+GLONASS +BeiDou,

$$\begin{aligned}
P_{r,IF}^{j,G} + cd\overline{t}_{IF}^{j,G} &= \overline{\rho}_{r}^{j,G} + c \cdot d\overline{t}_{r}^{G} + m_{r}^{j,G} \cdot ZTD + \varepsilon_{r,P_{IF}}^{j,G} \\
L_{r,IF}^{j,G} + cd\overline{t}_{IF}^{j,G} &= \overline{\rho}_{r}^{j,G} + c \cdot d\overline{t}_{r}^{G} + m_{r}^{j,G} \cdot ZTD + \overline{\mathrm{N}}_{r,IF}^{j,G} + \varepsilon_{r,L_{IF}}^{j,G} \\
P_{r,IF}^{j,R} + cd\overline{t}_{IF}^{j,R} &= \overline{\rho}_{r}^{j,R} + (c \cdot d\overline{t}_{r}^{G} + ISB_{r}^{j,GR}) + m_{r}^{j,R} \cdot ZTD + \varepsilon_{r,P_{IF}}^{j,R} \\
L_{r,IF}^{j,R} + cd\overline{t}_{IF}^{j,R} &= \overline{\rho}_{r}^{j,R} + (c \cdot d\overline{t}_{r}^{G} + ISB_{r}^{j,GR}) + m_{r}^{j,R} \cdot ZTD + \overline{\mathrm{N}}_{r,IF}^{j,R} + \varepsilon_{r,L_{IF}}^{j,R} \\
P_{r,IF}^{j,B} + cd\overline{t}_{IF}^{j,B} &= \overline{\rho}_{r}^{j,B} + (c \cdot d\overline{t}_{r}^{G} + ISB_{r}^{GB}) + m_{r}^{j,G} \cdot ZTD + \varepsilon_{r,P_{IF}}^{j,B} \\
L_{r,IF}^{j,B} + cd\overline{t}_{IF}^{j,B} &= \overline{\rho}_{r}^{j,B} + (c \cdot d\overline{t}_{r}^{G} + ISB_{r}^{GB}) + m_{r}^{j,B} \cdot ZTD + \overline{\mathrm{N}}_{r,IF}^{j,B} + \varepsilon_{r,L_{IF}}^{j,B}
\end{aligned} \tag{8}$$

where ISB_{r}^{GB} denote the ISB parameters of GPS-BeiDou, which is only dependent on satellite system not frequency because that BeiDou satellite systemis adopted to the Code Division Multiple Access (CDMA) scheme. Whereas, GLONASS signals are generated based on FDMA scheme and thus the ISB for GPS-GLONASS $ISB_{r}^{j,GR}$ are different for each satellite for a tracking station.

3. Test Results and Analysis

3.1 Data collections and processing strategy

To validate the above-mentioned mathematical model and evaluate the performance of multi-constellation PPP in Australia, three GNSS reference stations equipped with dual frequency receiver capable of multi-GNSS tracking from the Victorian Continuously Operating Reference Stations (CORS) network - GPSnet were selected. The stations were Benalla (BNLA), Marengo (MNGO) and Worri-Yallock (WORI). Seven days of GNSS observations from 9-15 January 2015 (DOY 009 to 015) were recorded at a sampling rate of 30-second. These GPSnet stations support tracking of GPS, GLONASS, and BeiDou constellations and their information are provided in Table 2.

Table 2. Information of the GNSS stations.

Station	Receiver Type	Antenna	ITRF08 Coordinates (dd.mmsssssss)		
			Latitude	Longitude	Ellipsoidal Height
BNLA	TRIMBLE NETR9	TRM57971.00	-36.323789799	146.002148938	187.452
MNGO	TRIMBLE NETR9	TRM59800.00	-38.464726718	143.390618770	62.694
WORI	TRIMBLE NETR9	TRM57971.00	-37.463748052	145.314810106	117.955

In this study, an extended Kalman Filter was used to estimate the state parameters. The parameters estimated at each epoch were the receiver position information (dx, dy, dz), the receiver clock error (dt_r), the tropospheric zenith delay (ZTD), and tropospheric gradient in the NS and EW directions, as well as the float carrier phase ambiguities (N). The receiver dynamic coordinates and clock are modelled as Random Walk (Zumberge et al.,1997; Larson et al., 2003; Li et al., 2013; Grover and Hwang, 1992). The ambiguity is estimated as a constant if no cycle slips are detected over time. Meanwhile, the static coordinates, ISB and IFB are assumed to be constant (Li and Zhang et al., 2015). The tropospheric zenith wet delay is modelled as a random walk process. All satellite systems' precise orbit and clock products were obtained from Deutsches GeoForschungsZentrum (GFZ), which is an IGS MGEX Analysis Centre (Table 1). The Phase Centre Offset (PCO) and Phase Centre Variation (PCV) for satellite and receiver of GPS and GLONASS were corrected using the IGS antenna products (IGS, 2015b). However, there is presently no available antenna products for BeiDou, thus PCO only can be corrected using conventional antenna offsets for these satellite (BeiDou about [0.2,0,0.6] in meters (IGS, 2015c)). PCV for satellite antennas and PCO as well as PCV corrections in the receiver side were not taken into consideration in the processing. The station displacement (i.e., solid Earth tides, ocean tides, solid Earth pole tides and relativistic effects) models suggested by the IERS conventions (Petit and Luzum, 2010) and the phase-wind up effects model (Wu et al., 1993) were also applied. All solutions were aligned to the IGS08 reference frame and GPS time was used as the reference time. The details of the multi-GNSS PPP processing strategy are listed in Table 3.

Table 3. The strategies for Multi-Constellations (GPS/GLONASS/BeiDou) PPP.

Item	Models/Constraints
Observations	- Ionosphere-free combination measurements - GPS: L1/L2; GLONASS: L1/L2; BeiDou: B1/B2 - Elevation-dependent weighting strategy
Elevation Angle Cut-off	- 7°
Sampling Rate	- 30s
Precise Satellite Orbit	- GFZ precise orbit products（gfmyyyyd.sp3：15min）
Precise Satellite Clock	- GFZ precise clock products（gfmyyyyd.clk：5min）
Satellite PCO	- GPS+GLONASS：IGS antenna products（IGS08.atx） - BeiDou: Conventional Antenna Offsets (http://igs.org/mgex/status-BDS）
Satellite PCV	- GPS + GLONASS: IGS antenna products (IGS08.atx) - BeiDou: not applied
Receiver PCO and PCV	- GPS + GLONASS: IGS antenna products (IGS08.atx) - BeiDou: Not applied.
Phase wind-up	- Corrected (Wu et al.,1993)
Ionosphere	- First order effect removed by ionosphere-free combination
Troposphere model	- Saastamoinen model
Displacement	- Solid earth tides, solid earth pole tides ,ocean tides and

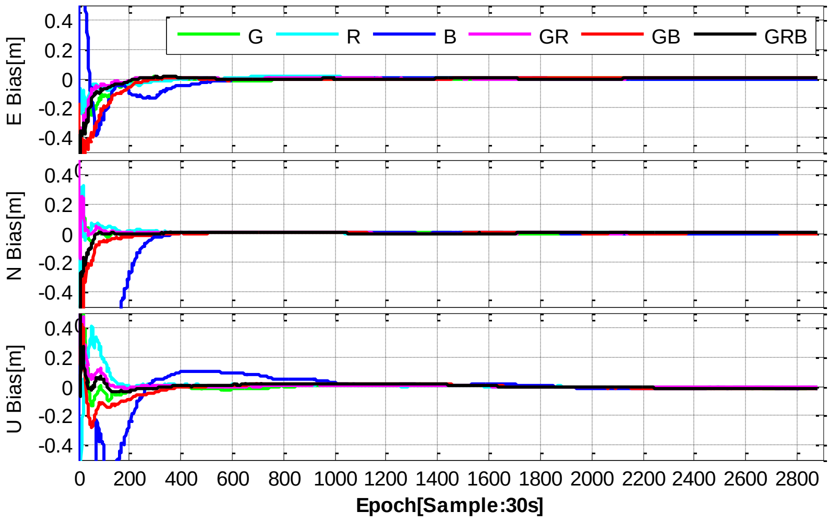
	relativistic effects modelling by IERS Convention 2010
Reference time system	- GPS Time
Station position	- Static: Constant - Kinematic: A Random Walk process for each epoch at a rate of 100m/s - An initial uncertainty of 100m
Receiver clock error	- A Random Walk process for each epoch at a rate of 100m/s - An initial uncertainty of 300km
Troposphere delay	- A Random Walk process for each epoch at a rate of 36cm/h - An initial uncertainty of 0.15 m
Ambiguity	- Constant for each satellite arc
System time difference	- A Random Walk process for each epoch at a rate of 100m/s

3.2 Static PPP Results

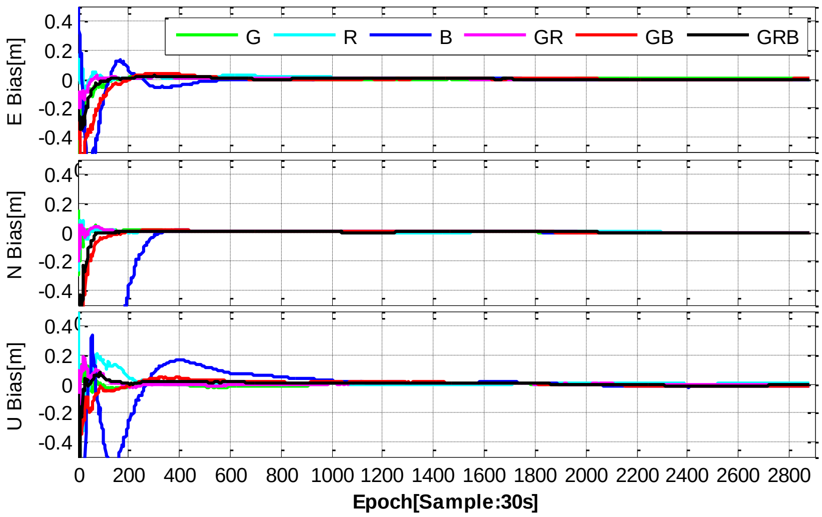
Figure 3 shows the PPP positional errors time series in the East, North and Up components for BLNA, MNGO and WORI stations on 11 January 2015 as an example. The positional errors were computed based on the differences between the estimated PPP solution and the known station coordinates. The symbols G, R and B in the figure denote the abbreviations of GPS, GLONASS and BeiDou, respectively. It can be seen that the combined triple-constellation PPP, i.e., GPS+GLONASS+BeiDou, shows the highest precision and the fastest convergence in all of the three position components. The performance of GPS-only PPP is better than the other single constellation system. Conversely, BeiDou-only PPP required longer convergence time and the up component converged significantly slower than the east component. However it should be noted that comparable positioning accuracy could be obtained in the case of BeiDou-only PPP after a long solution convergence time.

Table 4 presents the RMS values (3 sigma) in metres and the measured convergence time in minutes for six processing scenarios: GPS-only, GLONASS-only, BeiDou-only, GPS+GLONASS, GPS+BeiDou, GPS+GLONASS+BeiDou. The statistics were computed using all seven days of data. In this study, the static position filter is considered to have converged when the positioning errors in all directions reach ±0.05 m and remain within ±0.05 m. The convergence time can be interpreted as the period from the first solution epoch to the converged epoch.

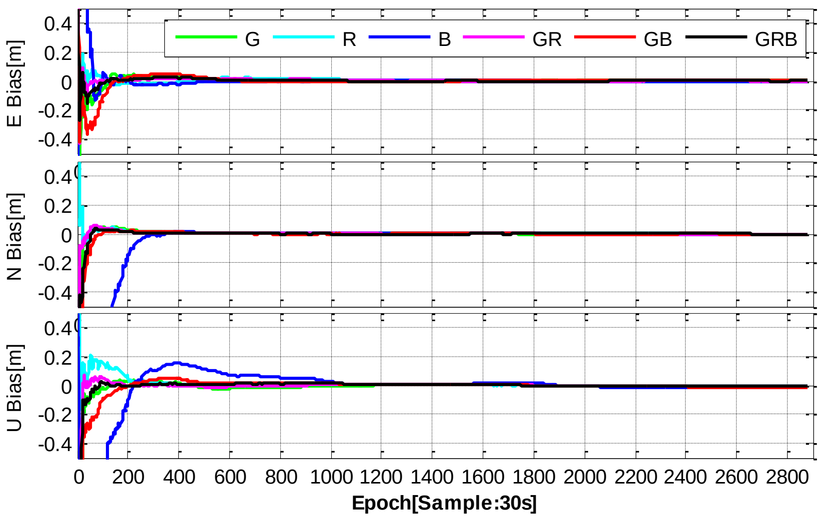
It can be inferred from Table 4 that the combined GPS+GLONASS, GPS+BeiDou and GPS+GLONASS+BeiDou PPP show relatively faster convergence time and higher position accuracy in every component as compared to a single-constellation solution, especially GLONASS-only and BeiDou-only PPP. For the single-constellation solution, GPS-only PPP solution has already reached a high accuracy position result under 7° cut-off elevation angle because the number of visible satellites for GPS is sufficient for positioning. However, the BeiDou-only PPP has poorer accuracy than the GPS-only and GLONASS-only solution. In fact, it did not provide any contribution to the combined GPS+BeiDou or GPS+GLONASS+BeiDou solutions because of the BeiDou orbital errors caused by the Inclined Geosynchronous Orbit (IGSO) satellites and Geostationary Orbit (GEO) satellites. These errors are results of the satellites having small geometric changes relative to the tracking stations on the ground, as well as the number and distribution of the global tracking stations used to compute the orbits is relatively small and uneven. It is envisioned that the quality of the BeiDou satellite orbits and clock products will improve in the future as the distribution and number of ground tracking stations increase. This will be of great benefit to improving the accuracy and convergence time of PPP (Geng et al., 2010; Li and Qu, 2014).



(a) BNLA



(b) MNGO



(c) WORI

Figure 3. Differences in position between different static PPP positioning solutions, i.e., GPS-only, GLONASS-only, BeiDou-only, GPS+BeiDou, GPS+GLONASS, GPS+GLONASS+BeiDou, for

BNLA, MNGO and WORI GNSS stations on 11 January 2015.

Table 4. RMS (3 sigma) in centimetres and convergence time in minutes for the daily static PPP solutions.

Station	Item	GPS	GLO	BDS	GPS+GLO	GPS+BDS	GPS+GLO +BDS
BNLA	Time (<5cm)	58min	100min	502min	53min	60min	51min
	East	1.1	1.2	0.7	0.4	0.6	0.3
	North	0.3	0.3	0.6	0.3	0.1	0.2
	Up	1.5	1.0	5.7	1.1	2.4	2.1
	2-D	1.1	1.2	0.9	0.5	0.6	0.3
	3-D	1.9	1.6	5.7	1.2	2.5	2.1
MNGO	Time (<5cm)	65min	105min	400min	51min	66min	50min
	East	0.5	1.7	0.7	0.6	0.5	0.4
	North	0.6	0.3	0.6	0.5	0.5	0.4
	Up	1.3	0.6	5.5	0.7	2.2	1.5
	2-D	0.8	1.7	0.9	0.7	0.6	0.6
	3-D	1.5	1.8	5.5	1.0	2.3	1.6
WORI	Time (<5cm)	51min	101min	412min	52min	74min	37min
	East	0.5	1.6	0.6	0.9	0.6	0.5
	North	0.3	0.2	0.2	0.2	0.2	0.2
	Up	1.2	1.0	1.8	0.7	1.8	1.6
	2-D	0.5	1.6	0.6	0.9	0.6	0.5
	3-D	1.3	1.9	1.9	1.1	1.9	1.6

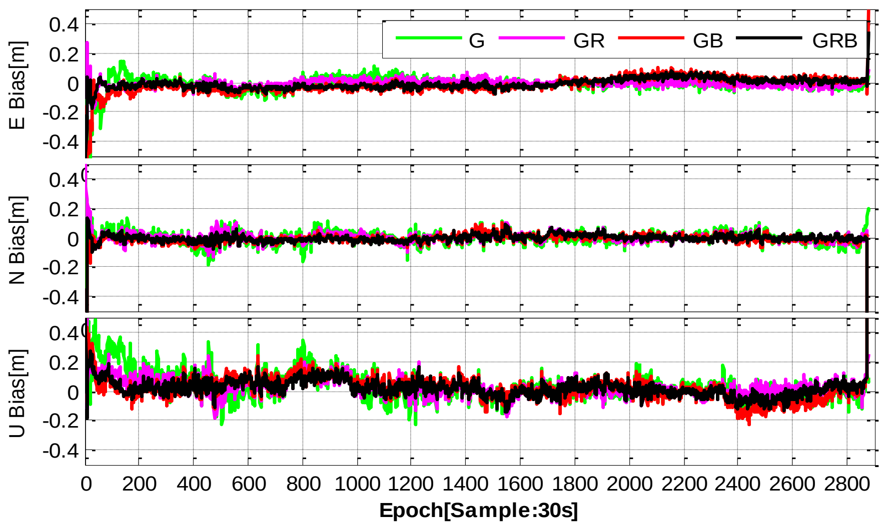
3.3 Kinematic PPP Results

To assess kinematic PPP in a multi-GNSS scenario, the same dataset used in static processing was used to simulate kinematic processing mode. Figure 4 shows the a daily time series of the kinematic PPP results in the East, North and Up components for single- and combined-constellation at BNLA, WORI and MNGO stations on January 11, 2015. The green, pink, red and black lines represent the kinematic PPP results for GPS-only, GPS+GLONASS, GPS+BeiDou and GPS+GLONASS+BeiDou, respectively (GLONASS-only and BeiDou-only PPP solutions are not presented as they showed less than ideal results). Figure 4 show that the combined GPS+GLONASS+BeiDou PPP solutions have the shortest convergence time as well as improved positioning accuracy than the GPS-only PPP solution.

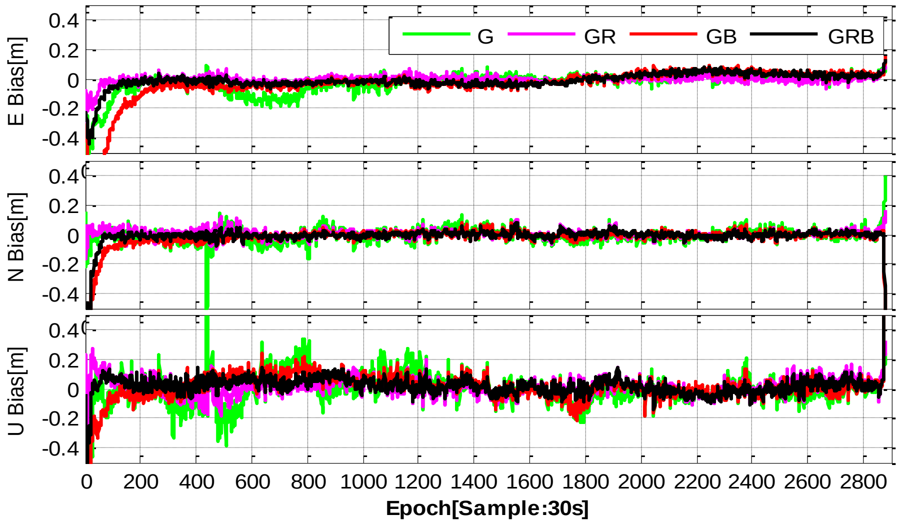
Table 5 presents the mean convergence time and RMS values (3 sigma) in East, North and Up components after convergence of the positioning results using seven consecutive days. The convergence criterion for the kinematic PPP is that the positioning errors reach ±0.20 m and remain within ±0.20 m. It can be inferred from Table 5 that the GPS+GLONASS+BeiDou PPP significantly improves the PPP performance compared to the GPS-only solution with an average accuracy improvements of 20% and 30% in the horizontal and vertical components, respectively. The positioning accuracy for the combined GPS+GLONAS+BeiDou PPP solutions is better than 48 cm after a convergence time. As for the convergence time, all cases can achieve accuracy level of better than 20 cm with less than 90 minutes. The combined GPS+BeiDou and GPS+GLONASS solutions significantly shorten the convergence time compared to the single-constellation GPS-only solution by about 23% and 20%. The combined GPS+GLONASS+BeiDou PPP solution shows the fastest convergence time, i.e., the solutions took about 32~48 minutes to converge. In addition, the positioning accuracy of all cases in the horizontal component is better than the vertical component which is expected.

Table 5. RMS (3 sigma) in centimetres and convergence time in minutes for the daily kinematic PPP solutions.

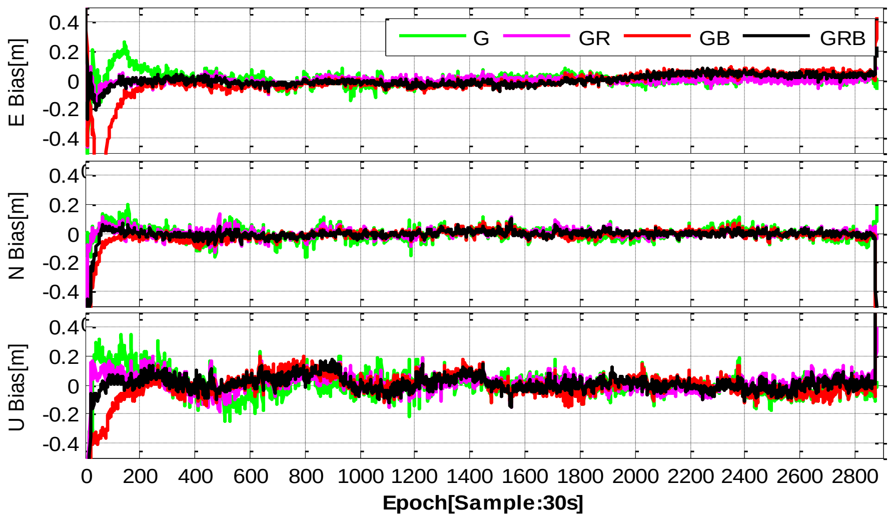
Station	Item	GPS	GPS+BDS	GPS+GLO	GPS+GLO+BDS
BNLA	Time (<20cm)	85min	68min	42min	41min
	East	5.4	6.7	3.6	5.3
	North	5.9	3.7	4.3	3.4
	Up	12.8	12.4	9.5	9.0
	2-D	8.0	7.6	5.7	6.3
	3-D	15.1	14.6	11.0	11.0
MNGO	Time (<20cm)	89min	62.5min	45min	48min
	East	8.7	7.0	3.2	6.5
	North	6.3	3.4	3.9	3.0
	Up	15.1	10.8	8.5	8.0
	2-D	10.8	7.7	5.0	6.5
	3-D	18.6	13.3	9.9	10.3
WORI	Time (<20cm)	74min	65min	35min	32min
	East	4.8	6.9	3.2	5.6
	North	5.8	3.7	4.1	3.0
	Up	10.6	10.2	8.3	8.3
	2-D	7.5	7.8	5.2	6.3
	3-D	13.0	10.2	9.8	10.4



(a) BNLA



(b) MNGO



(c) WORI

Figure 4. Differences in position between different kinematic PPP positioning solutions, i.e., GPS-only, GLONASS-only, BeiDou-only, GPS+BDS, GPS/GLONASS, GPS/GLONASS/BDS) for BNLA, MNGO and WORI GNSS stations on 11 January 2015.

4. Conclusion

The advent of multi-constellation satellite systems, such as Russia's GLONASS and China's BeiDou offers additional satellites and observables, which can strengthen the positioning model thereby improving the accuracy and convergence time of PPP. This paper describes the performance of GPS+GLONASS+BeiDou PPP in both static and kinematic modes. A multi-constellation GNSS PPP software for processing GPS, GLONASS and BeiDou observations was developed in this study. The performance and the benefits of a combined GPS+GLONASS+BeiDou PPP system were evaluated and compared using data collected from the three Victorian CORS network (GPSnet) in Australia. The combined multi-constellation (GPS+GLONASS+BeiDou) kinematic PPP improves the positioning accuracy and shortens the convergence time by about 20% when compared to a single-constellation system PPP, e.g., GPS-only. Meanwhile, the time series of the multi-constellation PPP were more stable than a single constellation PPP solution, i.e., GPS-only solution. With the modernisation of GLONASS and the advancement of BeiDou, Galileo and other satellite navigation systems in the near future, it is anticipated that multi-GNSS PPP will provide higher positioning accuracy, more reliable and available service to support high accuracy GNSS applications and scientific research.

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