doi:10.3772/j.issn.1006-6748.2020.03.001

Comparison of availability and reliability among different combined-GNSS/RNSS precise point positioning①

Chen Jian (陈 健), Yue Dongjie②, Zhu Shaolin, Liu Zhiqiang, Dai Jianbiao
(School of Earth Science and Engineering, Hohai University, Nanjing 211100, P. R. China)

Abstract

With emergence of the BeiDou Navigation Satellite System (BDS), the Galileo Satellite Navigation System (Galileo), the Quasi-Zenith Satellite System (QZSS) and the restoration of the Global Navigation Satellite System (GLONASS), the single Global Positioning System (GPS) has been gradually expanded into multiple global and regional navigation satellite systems (multi-GNSS/RNSS). In view of differences in these 5 systems, a consolidated multi-GNSS/RNSS precise point positioning(PPP) observation model is deduced in this contribution. In addition, the performance evaluation of PPP for multi-GNSS/RNSS is conducted using a large number of the multi-GNSS experiment (MGEX) station datasets. Experimental results show that multi-GNSS/RNSS can guarantee plenty of visible satellites effectively. Compared with single-system GPS, PDOP, HDOP, and VDOP values of the multi-GNSS/RNSS are improved by 46.8%, 46.5% and 46.3%, respectively. As for convergence time, the static and kinematic PPP of multi-GNSS/RNSS are superior to that of the single-system GPS, whose reliability, availability, and stability drop sharply with the increasing elevation cutoff. At satellite elevation cutoff of 40°, the single-system GPS fails to carry out continuous positioning because of the insufficient visible satellites, while the multi-GNSS/RNSS PPP can still get positioning solutions with relatively high accuracy, especially in the horizontal direction.

Key words: precise point positioning (PPP), positioning accuracy, convergence rate, multiple global and regional navigation satellite systems (multi-GNSS/RNSS), reliability and availability

0 Introduction

Precise point positioning (PPP) on the basis of global positioning system (GPS) has such advantages as absence of ground reference station, independence of baseline length, and high precision of coordinates[1], which endow it with wide applications like satellite geometric orbit determination[2], monitoring of bridge[3], earthquake monitoring and warning [4], etc. At present, positioning accuracy at centimeter and decimeter level can be achieved for static and kinematic PPP of single-system GPS. However, its intolerable convergence time that impedes the achievement of high positioning accuracy exists as a major drawback. On such basis, the multiple global navigation satellite system (GNSS) integration is considered a valid measure to improve convergence speed and reduce consequently the time needed for convergence.

Following the modernization of American GPS, the restoration of Russian Global Navigation Satellite System (GLONASS), and also developments of Chinese BeiDou Navigation Satellite System (BDS), European Galileo Satellite Navigation System (Galileo), and Japanese Quasi-Zenith Satellite System (QZSS), the positioning stability, reliability, and availability of PPP solution are all much enhanced by multiple global and regional navigation satellite systems (multi-GNSS/RNSS) especially in challenging environments like urban areas and ravines[5-7]. Therefore, the multi-GNSS/RNSS PPP will become the developing trend of GNSS precise positioning in the future. The combination PPP research is originally established on the combined dual-system of GPS/GLONASS. Functional and stochastic models of the integrated GPS/GLONASS PPP have been deduced based on the ionosphere-free observation model. The test results suggested that in spited of an enhanced convergence speed, the combined PPP still showed equal positioning accuracy as that of the single-system GPS PPP[8]. On the other hand, improvements

① Supported by the National Natural Science Foundation of China (No. 41604018), the Fundamental Research Funds for the Central Universities (No. 2019B17514) and Postgraduate Research & Practice Innovation Program of Jiangsu Province (No. nos. sjky19_0513, 2019B60114).

② To whom correspondence should be addressed. E-mail: 861159024@qq.com

Received on Aug. 4, 2019

in both positioning accuracy and convergence time of PPP under challenging conditions (limited GPS satellites) could be realized by integration of GLONASS and GPS[9]. Meanwhile, the integrated dual-system GPS/GLONASS PPP could enhance the accuracy of initial ambiguity solution and then shorten the ambiguity fixed timing for PPP[10,11]. Since December 27, 2012, the Chinese BDS has been servicing the Asia-Pacific region for positioning, navigation, and timing. Slight deterioration has been observed in the combined GPS/BDS PPP compared with single GPS system, resulting probably from the multipath of BDS GEO satellites[12]. PPP of the combined three-system GPS/GLONASS/BDS possesses better convergence time than single-system GPS or single-system GLONASS does, but no apparent enhancement for positioning accuracy has been observed using the processed daily data[13]. But gratifyingly, PPP solution of the combined four-system GPS/GLONASS/BDS/Galileo can realize enhanced reliability and availability in challenging environments relative to the single-system GPS PPP[14-16]. Recently, QZSS has attracted more research attentions thanks to its increasing development and application. Its signal design and orbit characteristics and signal design has been introduced[17], while its noise, signal to noise ratio as well as the multipath error are evaluated according to the measurement data in international GNSS service (IGS). QZSS performance in China region has been analyzed from 3 aspects, i.e. signal accuracy, availability, and kinematic PPP[18]. For the moment, many studies are mainly focused on single-system QZSS, dual-system GPS/GLONASS, dual-system GPS/BDS, and three-system GPS/GLONASS/BDS. Further evaluation on the performance of the latest five-system GPS/GLONASS/BDS/Galileo/QZSS PPP is still in need.

In this contribution, the observation model and data processing strategy of PPP in the five-system GPS/GLONASS/BDS/Galileo/QZSS are expounded subsequently in Section 1. Afterwards, the kinematic and static multi-GNSS/RNSS PPP solution is mainly evaluated via data from 6 MGEX reference stations in Section 2, with respect to the accuracy of positioning and timespan needed for convergence. Finally, important conclusions accompanied by experimental results are summarized briefly in Section 3.

1 Multi-GNSS/RNSS PPP model

1.1 Multi-GNSS/RNSS PPP observation model

In PPP, the first-order ionospheric delay is usually eliminated by the ionosphere-free (IF) pseudo-range and phase observation. The equation is as follows.

$$\begin{cases} P_i^s = \rho_r^s + c \cdot (\delta t_r - \delta t^s) + T^s + \sum \varepsilon_p \\ L_i^s = \rho_r^s + c \cdot (\delta t_r - \delta t^s) + T^s + \lambda_i N_i^s + \sum \varepsilon_L \end{cases} \quad (1)$$

where, s, i, and r denote different satellites, carrier frequencies, and receivers, respectively; ρ_r^s represents the geometric distance while c is the fixed symbol for light speed; δt_r and δt^s refer to clock errors of the receiver and satellite, respectively; N_i^s is recorded for the parameter of ambiguity while λ_i represents the wavelength at various frequencies; $\sum \varepsilon_P$ and $\sum \varepsilon_L$ are the total of measurement noises and multipath errors, respectively.

Considering the inter-system bias (ISB) of different systems, the observation model of multi-GNSS PPP can be obtained.

$$\begin{cases} P_i^{s,G} = \rho_r^s + c \cdot (\delta t_r - \delta t^s) + T^{s,G} + \sum \varepsilon_p \\ L_i^{s,G} = \rho_r^s + c \cdot (\delta t_r - \delta t^s) + T^{s,G} + \lambda_i N_i^s + \sum \varepsilon_L \\ P_i^{s,R_k} = \rho_r^s + c \cdot (\delta t_r - \delta t^s + ISB_r^{s,R_k}) + T^{s,R} + \sum \varepsilon_p \\ L_i^{s,R_k} = \rho_r^s + c \cdot (\delta t_r - \delta t^s + ISB_r^{s,R_k}) + T^{s,R} + \lambda_i N_i^s \\ \quad + \sum \varepsilon_L \\ P_i^{s,C} = \rho_r^s + c \cdot (\delta t_r - \delta t^s + ISB_r^C) + T^{s,C} + \sum \varepsilon_p \\ L_i^{s,C} = \rho_r^s + c \cdot (\delta t_r - \delta t^s + ISB_r^C) + T^{s,C} + \lambda_i N_i^s \\ \quad + \sum \varepsilon_L \\ P_i^{s,E} = \rho_r^s + c \cdot (\delta t_r - \delta t^s + ISB_r^E) + T^{s,E} + \sum \varepsilon_p \\ L_i^{s,E} = \rho_r^s + c \cdot (\delta t_r - \delta t^s + ISB_r^E) + T^{s,E} + \lambda_i N_i^s \\ \quad + \sum \varepsilon_L \\ P_i^{s,J} = \rho_r^s + c \cdot (\delta t_r - \delta t^s + ISB_r^J) + T^{s,J} + \sum \varepsilon_p \\ L_i^{s,J} = \rho_r^s + c \cdot (\delta t_r - \delta t^s + ISB_r^J) + T^{s,J} + \lambda_i N_i^s \\ \quad + \sum \varepsilon_L \end{cases} \quad (2)$$

where, G, R, E, C, and J denote GPS, GLONASS, Galileo, BDS, and QZSS satellites, respectively; ISB_r^E, ISB_r^C and ISB_r^J stand for inter-system bias of Galileo, BDS and QZSS relative to GPS, which are irrelevant to the satellites. k refers to the frequency number of the GLONASS satellite. The ISB of GLONASS satellite relative to GPS, ISB_r^{s,R_k}, is related to the satellite. In comparison with GPS, GLONASS utilizes frequency division multiple access (FDMA) signals, which brings about frequency differences among GLONASS satellites. Therefore, GLONASS satellites possess different biases with varied frequencies[19-21].

1.2 Data processing strategy

In this contribution, the IF model, together with an extended Kalman filter, is applied to estimate parameters including receiver position, wet tropospheric delay, receiver clock error, ambiguities, and ISB. The phase center offset (PCO) and phase center variation (PCV) of GPS and GLONASS can refer to the ANTEX file released by IGS[22]. The satellite end PCO of BDS, Galileo, and QZSS is provided by the ANTEX file, while PCV at the satellite ends as well as PCO and PCV at the receiver ends can be found nowhere and thus not considered herein[23]. The observation, error correction, and estimation parameters are collected in Table 1.

Table 1 Processing strategy of static and kinematic PPP for the multi-GNSS/RNSS

Parameter		Model
Observation	Observation	Five-system pseudo-range and carrier phase observation
	Signal	GPS: L1, L2; GLONASS: L1, L2; BDS: B1, B2; Galileo: E1, E5a; QZSS: L1, L2
	Sampling rate	30 s
	Elevation cutoff	7 °
	Observation weight	Elevation-dependent weight
Error correction	Phase-windup effect	Corrected
	Receiver antenna phase center	PCO/PCV correctionis not considered
	Satellite antenna phase center	GPS/GLONASS: igs08.atx; Galileo/BDS/QZSS: PCO is corrected from MGEX while PCV correction is not considered
	Relativistic effect	Corrected
	Satellite orbit	MGEX precise orbit (15 min)
	Satellite clock	MGEX precise clock (30 s)
	Ionospheric delay	Ionosphere-free combination
	Dry tropospheric delays	Corrected
Parameter estimation	Receiver coordinates	Estimated (static and kinematic)
	Receiver clock	Estimated
	Phase ambiguities	Estimated
	ISB	Estimated
	Wet tropospheric delays	Estimated

2 Multi-GNSS/RNSS PPP performance analysis

The GNSS observations are recorded in 30 s intervals from 6 MGEX reference stations using date of October 20, 2016. The information of 6 MGEX stations are presented in Table 2. Performance evaluation and comparison of the single-GNSS and multi-GNSS/RNSS static and kinematic PPP solutions are established on data processing performed in the following 9 different GNSS combinations: single-system GPS PPP, single-system GLONASS PPP, single-system BDS PPP, single-system Galileo PPP, dual-system GPS/GLONASS PPP, dual-system GPS/BDS PPP, dual-system GPS/Galileo PPP, dual-system GPS/QZSS PPP, and five-system GPS/GLONASS/BDS/Galileo/QZSS PPP.

2.1 Availability of GNSS satellites

Observation data from the GMSD station on October 20, 2016 are selected for availability analysis of the single-system GPS and multi-GNSS/RNSS. Fig. 1 describes the visible satellite number, position dilution of precision (PDOP) values, horizontal dilution of precision (HDOP) values, and vertical dilution of precision (VDOP) values at elevation cutoff 10 °. The PDOP, HDOP, and VDOP values reflect the geometric distribution of satellites. Fig. 1 points out the following characteristics of GNSS satellites at the present stage.

1) For elevation cutoff of 10 °, the amount of visible satellites in GPS/GLONASS/BDS/Galileo/QZSS system is up to 30. Multiple constellations can provide abundant observation data, which improves the positioning accuracy consequently.

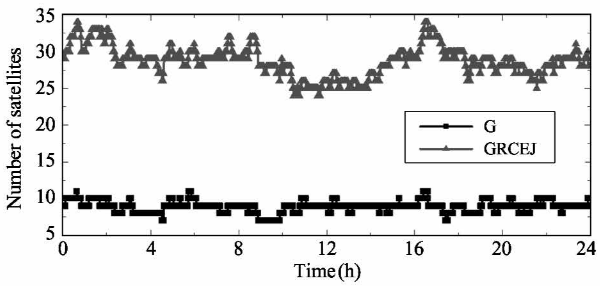
2) Statistics suggest that at least 7 GPS satellites,

6 GLONASS satellites, 8 BDS satellites, and 4 Galileo satellites are present in each epoch at the GMSD station.

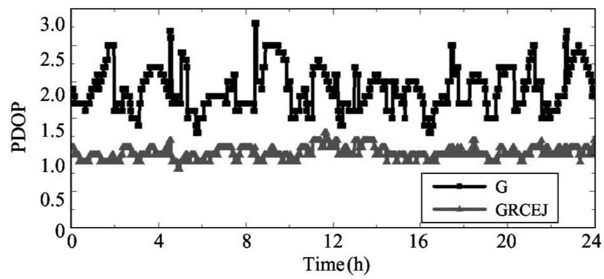
3) The averages of PDOP, HDOP, and VDOP values are 1.90, 0.99, and 1.62, respectively, for the single-system GPS, while decrease to 1.01, 0.53, and 0.87, respectively, for the combined GPS/GLONASS/BDS/Galileo/QZSS system, i. e. improvements of 46.8%, 46.5%, and 46.3%, respectively. Thus, the geometric strength of the positioning model is significantly enhanced by multi-GNSS/RNSS.

Table 2 Station information

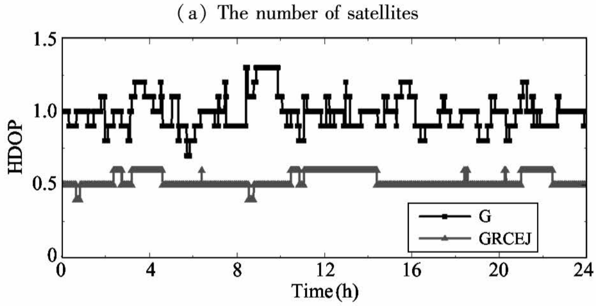
Station	Location	Longitude(°)	Latitude(°)	Receiver	Antenna	Systems
GMSD	Japan	131.02	30.56	Trimble NetR9	TRM59800.00 SCIS	GRCEJ
FTNA	French Polynesia	181.87	-14.30	Trimble NetR9	TRM59800.00 NONE	GRCEJ
NKLG	Gabon	9.67	0.35	Trimble NetR9	TRM59800.00 SCIS	GRCE
TLSE	France	1.48	43.56	Trimble NetR9	TRM59800.00 NONE	GRCE
JFNG	China	114.48	30.50	Trimble NetR9	TRM59800.00 NONE	GRCEJ
RGDG	Argentina	-67.75	-53.79	Trimble NetR9	TRM59800.00 SCIS	GRCE



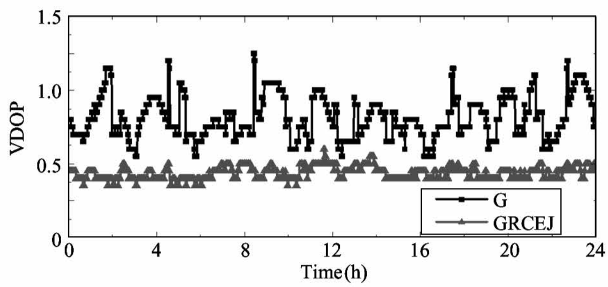
(a) The number of satellites



(b) PDOP value



(c) HDOP value



(d) VDOP value

Fig. 1 At GMSD station on October 20, 2016 (labels 'G', 'R', 'C', 'E', 'GR', 'GC', 'GE', 'GJ', and 'GRCEJ' denote the single-system GPS, single-system GLONASS, single-system BDS, single-system Galileo, dual-system GPS/GLONASS, dual-system GPS/BDS, dual-system GPS/Galileo, dual-system GPS/QZSS, and five-system GPS/GLONASS/BDS/Galileo/QZSS, respectively)

2.2 Static PPP

In this subsection, static PPP is processed with daily data of the 6 MGEX stations, followed by the analysis of positioning error and convergence time. Positioning error refers to the difference between positioning solution and IGS weekly solution. Subsequently, filtering convergence is defined when the positioning errors between the North and East components are less than 10 cm. Filtering is considered as converging at an epoch if the errors of positioning during the last 20 epochs remain within the limit. Fig. 2 demonstrates the static PPP solutions of single-system models and a combined GPS/GLONASS/BDS/Galileo/QZSS model at GMSD station. To compare the convergence time of PPP in single systems and the combined system, only results during the first 2 h are presented. Fig. 3 gives the positioning errors of the static PPP in the single-system and five-system models at different observation lengths (10 min, 15 min, 30 min, 1 h, 2 h, 4 h, 6 h, and 12 h).

According to Fig. 2, the timespan needed for convergence in the single-system GPS and GLONASS is

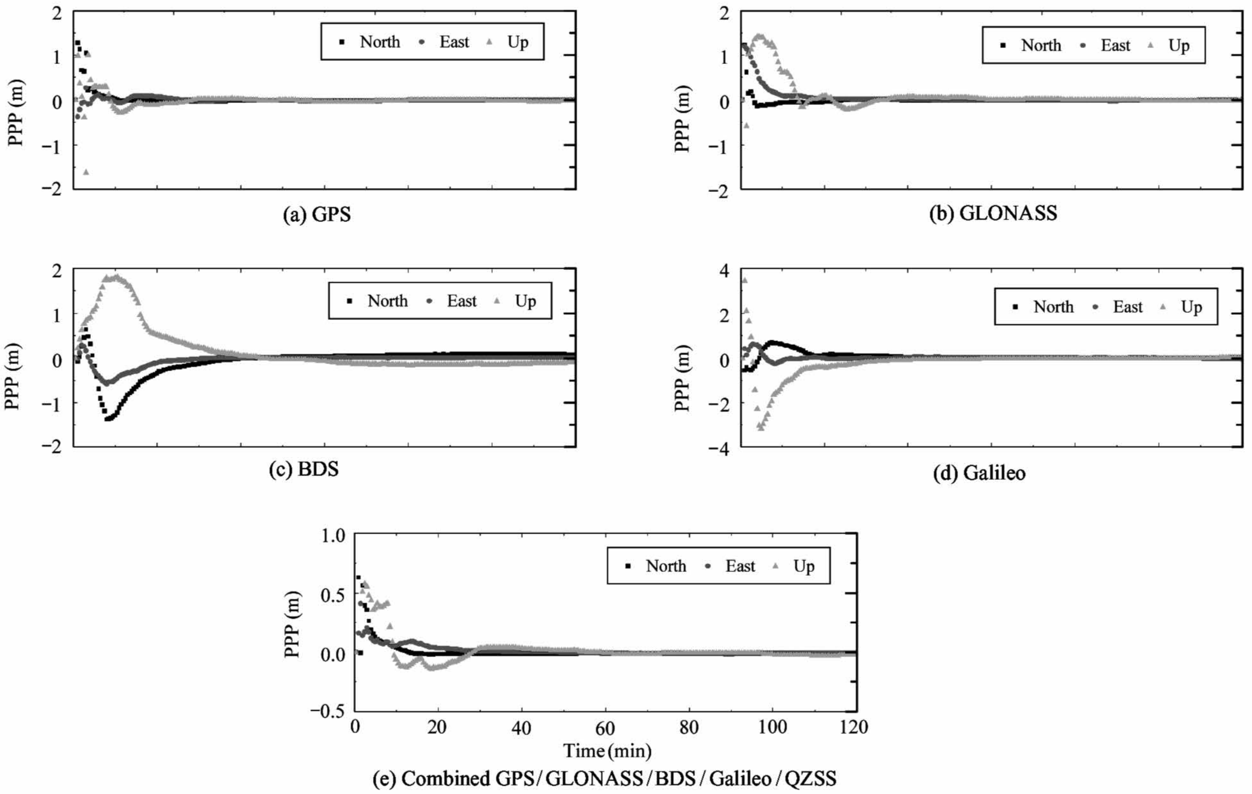


Fig. 2 Static PPP solutions of single-system and five-system models at GMSD station

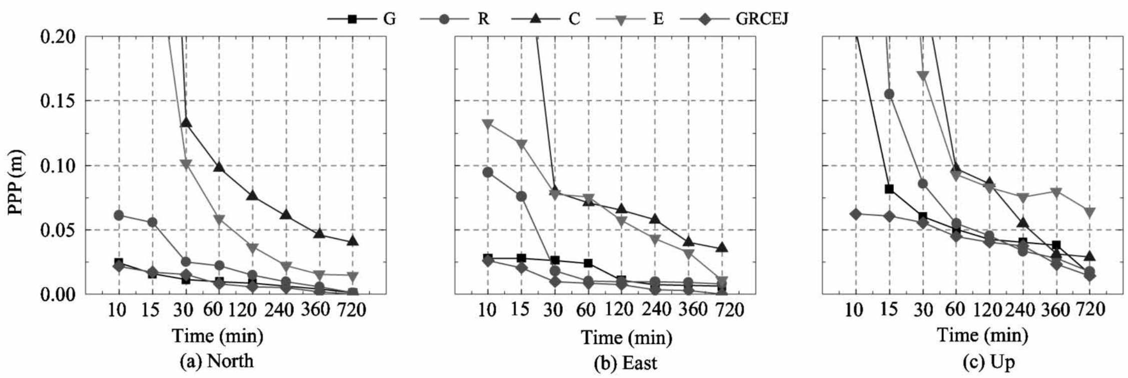


Fig. 3 Positioning errors of static PPP solutions with varied observation spans in single-system and five-system models

6.5 min and 9.5 min, respectively, which is shorter than the single-system BDS and Galileo at GMSD station. The convergence speed of the combined five-system GPS/GLONASS/BDS/Galileo/QZSS is the fastest, only 5.5 min, and the stability of the positioning solutions is improved. As shown in Fig. 3, higher positioning accuracy can be obtained by combined PPP with shorter time. For example, the positioning errors of static PPP reach 0.022 m, 0.026 m, 0.062 m with observation length of 10 min in the combined five-system GPS/GLONASS/BDS/Galileo/QZSS mode. Furthermore, the positioning error can converge to 1 cm in horizontal component and 5 cm in Up component within approximate 30 min, which is better than the results in single-systems. Since there is only one QZSS satellite, the positioning result is not given here.

To further evaluate the positioning error and convergence speed of the multi-GNSS/RNSS, daily solutions of 6 stations are statistically analyzed. Table 3 gathers the static PPP convergence time for the single and combined systems in each station, and Table 4 lists the corresponding positioning accuracy after daily data processing.

Table 3 indicates that PPP of single-system GPS and GLONASS shares equal average convergence time of about 18 min. At present, the clock and orbit products of BDS satellite hold relatively low precision, along with uncorrectable errors in PCO and PCV, which

Table 3 Static PPP convergence time of each station

Model	Convergence time (min)					
	GMSD	FTNA	JFNG	NKLG	TLSE	RGDG
G	6.5	36	19.5	16	14.5	15
R	9.5	25	18.5	27	14.5	16
C	31.5	70	60.5	72	65.5	36.5
E	34	73	68.5	82	74.5	43
GRCEJ/GRCE	5.5	13.5	15.5	15	3.5	10.5

Table 4 Static PPP positioning accuracy of each station (cm)

Station	G			R			C			E			GRCEJ/GRCE		
	North	East	Up	North	East	Up	North	East	Up	North	East	Up	North	East	Up
GMSD	0.6	0.9	2.4	0.7	0.8	3.4	1.1	1.0	2.9	1.8	2.6	3.8	0.4	0.8	2.2
FTNA	0.4	1.1	3.0	0.6	1.1	2.7	2.8	2.3	3.6	1.5	1.7	3.2	0.5	0.8	2.3
JFNG	0.3	1.4	3.9	0.9	0.7	3.8	3.6	2.6	4.2	1.6	3.0	5.0	0.4	0.7	2.8
NKLG	0.2	0.9	3.5	0.4	1.1	2.9	3.9	1.7	3.7	1.4	1.3	3.1	0.2	0.5	2.7
TLSE	0.7	0.9	2.2	0.6	0.2	3.9	2.4	2.0	4.2	1.8	1.5	7.8	0.5	0.6	2.5
RGDG	0.5	1.0	2.7	0.6	0.6	2.5	3.4	2.3	3.8	1.9	2.9	5.8	0.4	0.4	2.5

results in longer convergence time of BDS PPP, about 56 min. Single-system Galileo PPP gives convergence time of 62.5 min due to its poor geometric distribution. In comparison, the combined five-system GPS/GLONASS/BDS/Galileo/QZSS PPP wins out with the shortest average convergence time at about 10.5 min. The multi-GNSS/RNSS can provide users with plenty of available satellites and has a specific contribution to the improvement of single-GNSS positioning.

According to Table 4, the single-system GPS and GLONASS PPP solutions exhibit positioning errors better than 1.5 cm for horizontal components and better than 4 cm in the Up components. However, PPP solution in BDS gives inferior accuracy of positioning owing to less MEO satellites and lower precision of orbit and clock products. The positioning errors of the single-system BDS PPP solution are better than 4 cm for horizontal components and 5 cm in the Up component. Single-system Galileo PPP solution possesses the same positioning errors for horizontal components as BDS but errors better than 8 cm in the Up component due to its limited amount of available satellites at this stage. The average positioning errors of 0.4 cm, 0.6 cm, and 2.5 cm in North, East, and Up components are obtained by the combined five-system GPS/GLONASS/BDS/Galileo/QZSS PPP, respectively.

2.3 Kinematic PPP

The data processing strategy described in Section 2.2 is adopted to investigate kinematic PPP at every station, the calculated root mean square (RMS) values of kinematic PPP solutions in various models are plotted in Fig. 4.

According to Fig. 4, RMS of kinematic PPP solutions in the combined system are superior to those in the single-system GPS. As for combined dual-system, GPS/GLONASS shows better RMS values than GPS/BDS does mainly attributed to the inferior accuracy in BDS precise products to that in GLONASS precise products plus the uncorrectable PCO and PCV. However, GPS/BDS exhibits superior RMS values compared with GPS/Galileo and GPS/QZSS because there are fewer satellites in Galileo and QZSS systems. PPP results of the combined system can improve the positioning accuracy, especially for the five-system combination. Since single-system GNSS has already achieved high positioning accuracy (elevation cutoff of 10 °), the improvement of horizontal direction is limited, but accuracy at vertical direction can be enhanced significantly by combined systems.

Furthermore, the single-system GPS and multi-GNSS/RNSS PPP at different elevation cutoffs are processed for the purpose of simulating the challenging environments like urban areas. Kinematic PPP solutions obtained from single-system model and five-system model at GMSD station are compared at 2 different elevation cutoffs, as shown in Fig. 5.

Fig. 5 suggests that the influence of elevation cutoff on single-system GPS positioning is larger than on multi-GNSS, for the combined five-system GPS/GLONASS/BDS/Galileo/QZSS can still obtain high-accuracy positioning at elevation cutoff of 40 °. Moreover, the combined system owns higher stability than the single system does. Fig. 6 and Fig. 1(a) point out a dramatic

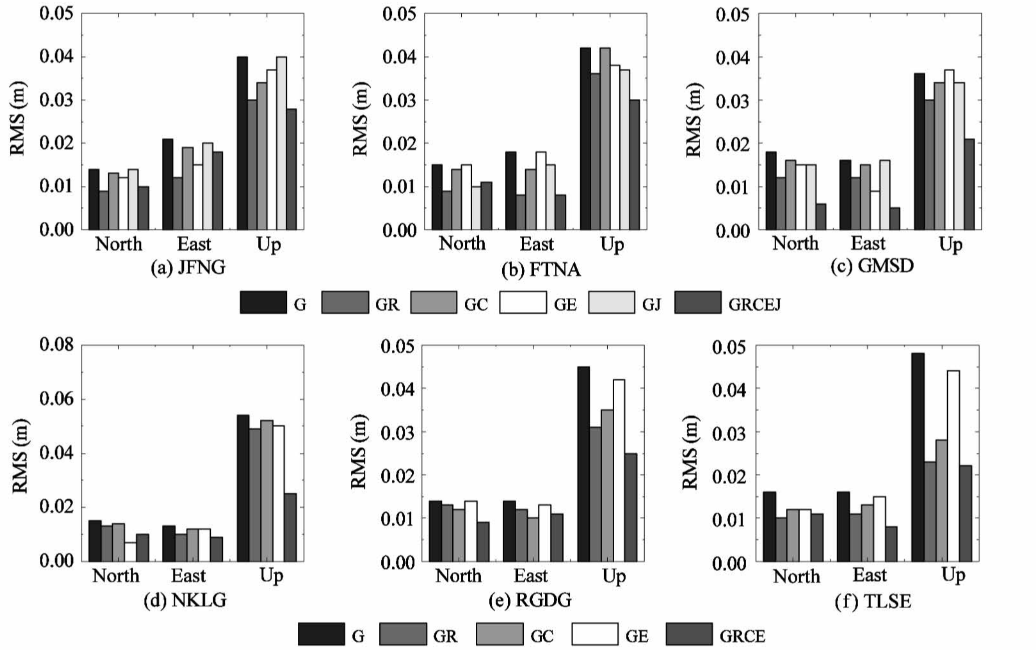


Fig. 4 Daily RMS values of single-system, dual-system, four-system, and five-system kinematic PPP solutions

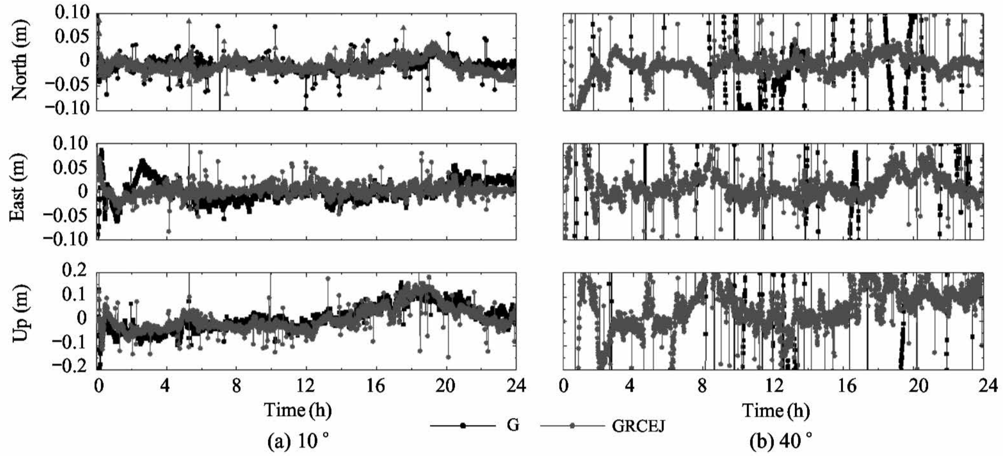


Fig. 5 Comparisons of PPP results in single-system and multi-GNSS/RNSS modes under elevation cutoff at GMSD station

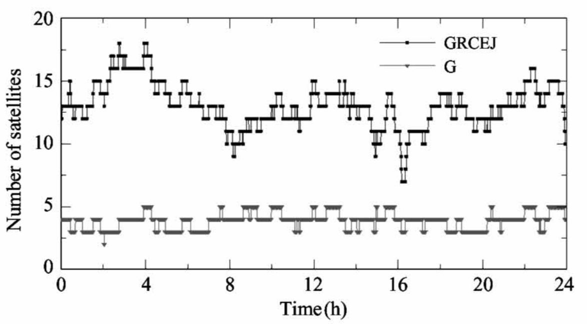


Fig. 6 The number of satellites under the 40 °elevation cutoff

decrease in the number of visible satellites for single system with increased elevation cutoff but more than 10 satellites in combined five-system GPS/GLONASS/BDS/Galileo/QZSS remained in every epoch under elevation cutoff from 10 ° to 40 °. This is the reason why the reliability, availability, and accuracy of the multi-GNSS/RNSS positioning are better than those of the single system.

3 Conclusions

Multi-GNSS/RNSS not only enriches the humdrum observation, but also enhances the geometrical strength of satellites, which is conducive to improving the positioning performance. The single system and combined GNSS static PPP experiments are carried out referring to the data obtained from MGEX reference stations, with primary focuses on the accuracy of positioning and the timespan needed for convergence. It is known that reliability, availability, and stability of GPS positioning drop sharply in complicated or bleak situations such as urban areas and valleys, as fewer satellites remain visible in these areas. Thus, the five-system PPP solutions under different elevation cutoffs are analyzed to demonstrate comprehensively the performance of multi-GNSS/RNSS positioning. Acquired experimental results are summarized below.

In comparison to the single-system GPS, PDOP, HDOP, and VDOP values obtained for the multi-GNSS/RNSS are improved by 46.8%, 46.5%, and 46.3%, respectively. In view of the obtained results, and convergence time and positioning accuracy of static PPP as well as kinematic PPP will be greatly improved when the single system holds a poor geometric configuration. At the GMSD station, it takes single-system GPS about 6.5 min to achieve the horizontal positioning accuracy of 10 cm, while the multi-GNSS/RNSS only spends 5.5 min. The positioning performance is associated closely with the elevation cutoff of the satellite, the single-system GPS of which deteriorates rapidly with increasing elevation cutoff. Differently, multi-GNSS/RNSS kinematic PPP is able to keep a centimeter-level positioning even at elevation cutoff of 40° with more stable solutions. This is of great practical significance for applications in mountainous areas or extremely sheltered areas.

References

[1] Zumbeger J F, Heflin M B, Jefferson D C, et al. Precise point positioning for the efficient and robust analysis of GPS data from large networks[J]. *Journal of Geophysical Research*, 1997, 102(B3):5005-5017

[2] Zhang X H, Li P, Zuo X. Kinematic precise orbit determination based on ambiguity-fixed PPP[J]. *Geomatics and Information Science of Wuhan University*, 2013, 38(9):1261-1265

[3] Chen J, Yue D J, Liu Z Q, et al. Experimental research on daily deformation monitoring of steel box girder bridge based on BDS/GPS[J]. *High Technology Letters*, 2018, 24(3):272-278

[4] Larson K M. Using 1-Hz GPS data to measure deformations caused by the Denali fault earthquake[J]. *Science*, 2003, 300(5624):1421-1424

[5] Geng J, Teferle F, Shi C, et al. Ambiguity resolution in precise point positioning with hourly data[J]. *GPS Solutions*, 2009, 13 (4):263-270

[6] Laurichesse D, Mercier F, Berthias J, et al. Integer ambiguity resolution on undifferenced GPS phase measurements and its application to PPP and satellite precise orbit determination[J]. *Navigation*, 2009,56(2):135-149

[7] Shi J, Gao Y. A comparison of three PPP integer ambiguity resolution methods[J]. *GPS Solutions*, 2014,18(4):519-528

[8] Cai C, Gao Y. Modeling and assessment of combined GPS/GLONASS precise point positioning[J]. *GPS solutions*, 2013, 17(2):223-236

[9] Martin A, Anquela A B, Capilla R, et al. PPP technique analysis based on time convergence, repeatability, IGS products, different software processing, and GPS + GLONASS constellation[J]. *Journal of surveying Engineering*, 2010, 137(3):99-108

[10] Jokinen A, Feng S, Schuster W, et al. GLONASS aided GPS ambiguity fixed precise point positioning[J]. *Journal of Navigation*, 2013, 66(3):399-416

[11] Li P, Zhang X. Integrating GPS and GLONASS to accelerate convergence and initialization times of precise point positioning[J]. *GPS Solutions*, 2014,18(3):461:471

[12] Zhao Q, Guo J, Li M, et al. Initial results of precise orbit and clock determination for BDS navigation satellite system[J]. *Journal of Geodesy*, 2013, 87(5):475-486

[13] Zhao X W, Wang S L, Liu C, et al. Assessing the performance of multi-GNSS precise point positioning in Asia-Pacific region[J]. *Empire Survey Review*, 2016, 49(354):186-196

[14] Li X, Ge M, Dai X, et al. Accuracy and reliability of multi-GNSS real-time precise positioning: GPS, GLONASS, BeiDou, and Galileo[J]. *Journal of Geodesy*, 2015,89(6):607-635

[15] Li X, Zhang X, Ren X, et al. Precise positioning with current multi-constellation Global Navigation Satellite Systems: GPS, GLONASS, Galileo and BeiDou[J]. *Scientific Reports*, 2016,5(1):8328-8330

[16] Cai C, Gao Y, Pan L, et al. Precise point positioning with quad-contellations: GPS, BeiDou, GLONASS and Galileo[J]. *Advances in Space Research*, 2016, 56(1):133-143

[17] Liao N H, Zhang Y, Lin B L, et al. The signal and service performance of the QZSS Navigation System[J]. *Geomatics and Spatial Information Technology*, 2013, 36(5):39-40

[18] Lou Y, Fu Z, Gong X, et al. Evaluation of QZSS system augmentation service performance in China region[J]. *Geomatics and Information Science of Wuhan University*, 2016, 41(3):298-302

[19] Ge M, Gendt G, Rothacher M, et al. Resolution of GPS carrier-phase ambiguities in precise point positioning (PPP) with daily observations[J]. *Journal of Geodesy*, 2007,82(7): 389-399

[20] Liu T, Yuan Y, Zhang B, et al. Multi-GNSS precise point positioning (MGPPP) using raw observations[J]. *Journal of Geodesy*, 2017, 91(3):253-268

[21] Liu Z Q, Wang J X, Duan B B. Estimation of GLONASS code inter-frequency biases with multiple parameters based on a single station and its impact on combined precise point positioning[J]. *Acta Geodaetica et Cartographica Sinica*, 2015,44(2):150-159

[22] Zhang B C, Ou J K, Yuan Y B. Precise point positioning algorithm based on original dual-frequency GPS code and carrier-phase observations and its application[J]. *Acta Geodaeticaet Cartographica Sinica*, 2010, 39(5): 65-72

[23] Ren X D, Zhang K K, Li X X, et al. Precise point positioning with multi-constellation satellite systems: BDS, Galileo, GLONASS, GPS[J]. *Acta Geodaeticaet Cartographica Sinica*, 2015, 44(12):1307-1339

Chen Jian, born in 1993. He is currently a Ph. D candidate at Hohai University. He received his M. S. degree from Anhui University of Science and Technology in 2016. His currently research mainly focuses on high precision positioning using GPS, BDS, and Galileo.