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ORIGINAL STUDY

Improving availability and accuracy of GPS/BDS positioning using QZSS for single receiver

Zengke Li[1] **· Fu Chen**[2]

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Abstract The Quasi-Zenith Satellite System (QZSS) service area covers East Asia and Oceania region and its platform is multi-constellation GNSS. The QZSS system is not required to work in a stand-alone mode, but together with data from other GNSS satellites. QZSS data is processed and analysed for single receiver together with GPS/BDS data in the paper. Single point positioning mode, static precise point positioning mode and kinematic precise point positioning mode are used to assess the impact of QZSS on GPS/BDS single receiver positioning. The data corresponding to the day 2015-02-05 taken from the IGS station of CUT0 is considered. The sky plots and number of satellite for the various satellite systems are given. The PDOP (Position Dilution of Precision) value, position error and solution success rate under different cut-off elevation angles are compared between GPS/BDS and GPS/BDS/QZSS. The results indicate that QZSS is able to decrease the position error and increase success rate of resolution for GPS/BDS single receiver positioning, especially under high cut-off elevation angle. The availability and accuracy of GPS/BDS positioning are improved using QZSS for single receiver.

Keywords Quasi-Zenith Satellite System · Single point positioning · Precise point positioning

1 Introduction

The Quasi-Zenith Satellite System (QZSS) is the Japanese regional satellite navigation system which provides positioning and timing information to users (Li and Rizos 2011). The Quasi-Zenith Satellite System service area covers East Asia and Oceania region.

✉ Fu Chen
chenfu_cumt@yeah.net

[1] School of Environment and Spatial Informatics, China University of Mining and Technology, Xuzhou, China

[2] Low Carbon Energy Institute, China University of Mining and Technology, Xuzhou, China

Recently, QZSS has been developed to enhance the performance of GNSS positioning, navigation and timing services.

Some research about QZSS has been carried out in recent years. The achievable performance of the GPS augmentation using QZSS were obtained using software simulation in 2004. The simulation analysis indicated that QZSS does not only effectively increase the availability and accuracy of GPS positioning, but also improve the reliability of GPS positioning in Japan and its neighbouring area (Wu et al. 2004). GPS availability and DOP performance were analysed in Seoul city center combining a geostationary satellite as well as QZSS with the conventional GPS. Using QZSS, a higher level of availability and more accurate user position were provided than when using GPS with a geostationary satellite (Yoo et al. 2009). Additions of QZSS to GPS, the average of the GPS/QZSS positioning solution horizontal error was 0.58 m, which shown an improvement of 52.8 % than the GPS-only solution (Li and Rizos 2011). The inclusion of the QZSS satellite in the rover has shown reductions of the order of 20 % in convergence time in the Asia Pacific region. At the same time the inclusion of the QZSS satellite represented an accuracy improvements of approximately 10 % in horizontal and 25 % in vertical (Landau et al. 2012). According to real-time positioning simulation, the navigation by QZSS could obtain horizontal accuracy of 10 m or better and vertical accuracy of 14 m or better with moderate user range error (Yamada et al. 2012). The carrier-to-noise density ratios from QZSS and GPS have been compared for a receiver in Chofu, Japan. Compared to GPS, the path loss of QZSS varied by about 1.5 dB because of the eccentricity of the orbit (Hauschild et al. 2012). With the GLONASS and QZSS augmentation to GPS-only processing shown improvements both for kinematic coordinate and ZTD solutions, especially in the period with lower number of GPS satellites (Iwabuchi et al. 2013). The RTK solutions during 24 h by GPS and GPS + QZSS observations shown that the resolutions were slightly better with one additional QZSS satellite augmentation (Lukes et al. 2013). The correction messages, such as orbits and clock information, could be delivered by the LEX signal of QZSS, which was use to realize precise point positioning (PPP) for real-time applications. The achievable PPP positioning accuracy in real-time using the current LEX corrections message could achieve the accuracy of decimetre level (Choy et al. 2013). Observations from the Chinese BeiDou Navigation Satellite System (BDS), European Galileo, American Global Positioning System (GPS) and the Japanese Quasi-Zenith Satellite System (QZSS) were combined to realize long baseline RTK positioning (Odolinski et al. 2014), 3D building model-based pedestrian positioning method (Hsu et al. 2015) and single-frequency RTK (Odolinski et al. 2015) and to analyse the robustness of single-frequency instantaneous carrier-phase attitude determination (Nadarajah and Teunieesn 2014) and receiver autonomous integrity monitoring (RAIM) performances (Su et al. 2014). L5-observables of multi-constellation GNSS formed from IRNSS, GPS, Galileo, and QZSS were evaluated for real-time kinematic positioning using the standard LAMBDA method. For single-frequency carrier phase-based positioning and navigation, the results shown better ambiguity resolution performance of L5/E5a-only processing than that of L1/E1-only processing (Nadarajah et al. 2015). Regional orbits and clocks for real-time PPP would be generated and delivered through the QZSS LEX signal. The real time PPP solutions using the developed 'Australian LEX' system have comparable performance to those obtained from the IGS real-time products through a land network, showing that latency and reliability of the system is adequate for real-time PPP (Harima et al. 2014). A new positioning method improving the availability and accuracy of Multi-global navigation satellites system (GNSS) positioning by using QZSS satellites in urban canyon environments was proposed. QZSS was regarded as the sole master satellite and the ambiguity of QZSS is fixed by the wide-lane method and the QZSS LEX signal (Kitamura et al. 2014).

In the present study, QZSS is used to improve the availability and accuracy of GPS/BDS single receiver positioning. The observation is process by single point positioning (SPP), static precise point positioning (PPP) and kinematic precise point positioning mode. The paper is divided into 5 sections. Following this introduction, the introduction of QZSS is overviewed in Sect. 2. Section 3 describes GPS/BDS positioning with QZSS, including SPP, static PPP and kinematic PPP. Test results are then presented and analysed in Sect. 4, followed by a summary of the main conclusions.

2 Quasi-Zenith Satellite System

The Quasi-Zenith Satellite System (QZSS), is a developing regional time transfer system and satellite based augmentation system for the Global Positioning System, which would be receivable within East Asia and Oceania region. The first satellite 'Michibiki' was launched on 11 September, 2010. After confirmation of the stability to provide specified performance in IS-QZSS, L1 C/A and L2C signals were set healthy on 22 June, 2011 and L5 and L1C signals were set healthy on 14 July, 2011. Four satellites constellation will be constructed and the service will be provided in 2018.

The QZSS aims at improving positioning accuracy of one meter to the centimeter level compared to the conventional GPS error of tens of meters by transmitting support signals. The Quasi-Zenith Satellites transmit signals compatible with the GPS L1C/A signal, as well as the modernized GPS L1C, L2C signal and L5 signals, which can provide seamless PNT (Positioning, Navigation and Timing) services by combining usage with GPS and increase coverage and availability of PNT services even in downtown and mountainous areas. QZSS also transmits two augmentation signals, i.e., L1-SAIF on 1575.42 MHz and LEX on 1278.75 MHz. The LEX signal can enhance GPS performance by transmitting error correction and integrity information.

The QZSS coordinate system is known as the Japan satellite navigation Geodetic System (JGS). This coordinate System is operated so as to approach International Terrestrial (ITRS). The time scale offset with the GPS is less than 2.0 m (95 %). The coordinate system offset with GPS is less than 0.02 m. Integer second offset for TAI is the same as GPS, and TAI is 19 s ahead of QZSST. The SV clocks of Quasi-Zenith Satellite (QZS) and GPS satellites are both controlled with respect to the offset with the GPS time scale (GPST). The Signal-in-Space (SIS) User Range Error is less than 1.6 m (95 %) without time and coordination offset error. The QZSS orbit parameter and tracking range is indicated in Table 1 and Fig. 1 shows the ground track of the QZSS.

Table 1 QZSS orbit parameter and tracking range

Orbit parameter	Nominal allocation	Tracking range
Semimajor axis	42,164 km	100
Eccentricity	0.075	0.075 ± 0.015
Inclination	40°	36–45°
Argument of perigee	270°	270 ± 2.5°
Central longitude	136°	130–140°

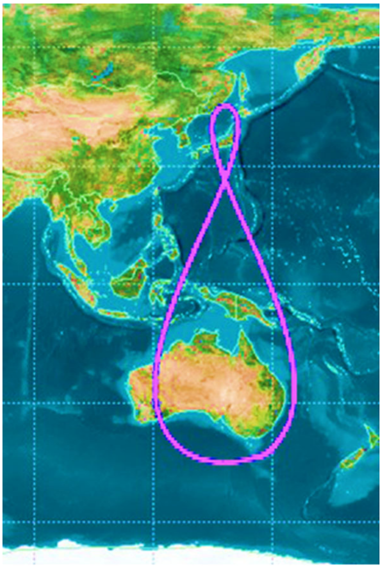

Fig. 1 The ground track of the QZSS

3 GPS/BDS positioning with QZSS

The traditional observation model of GNSS positioning, including the pseudorange and carrier phase measurements, can be written as (Du 2010):

$$P = \rho + c \times (dt - dt_s) + I + T + M_P + \varepsilon_P \tag{1}$$

$$\boldsymbol{\Phi} = \rho + c \times (dt - dt_s) - I + T + \lambda N + M_{\boldsymbol{\Phi}} + \varepsilon_{\boldsymbol{\Phi}} \tag{2}$$

where P and $\boldsymbol{\Phi}$ are the pseudorange and carrier phase measurements, respectively. ρ is the geometric distance as a function of receiver and satellite coordinates. c is the speed of light

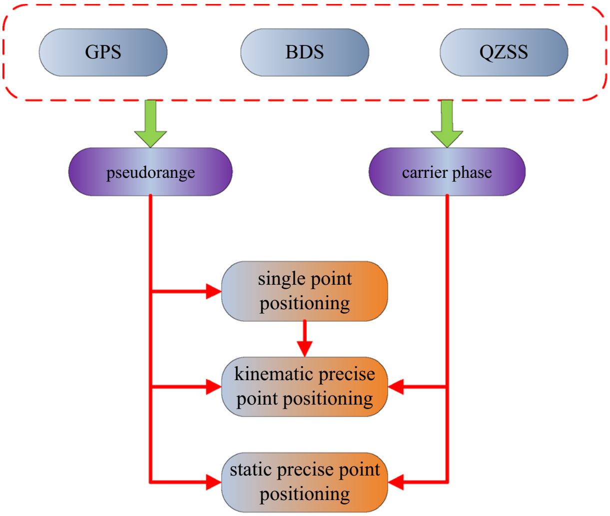

Fig. 2 Three positioning modes for single receiver

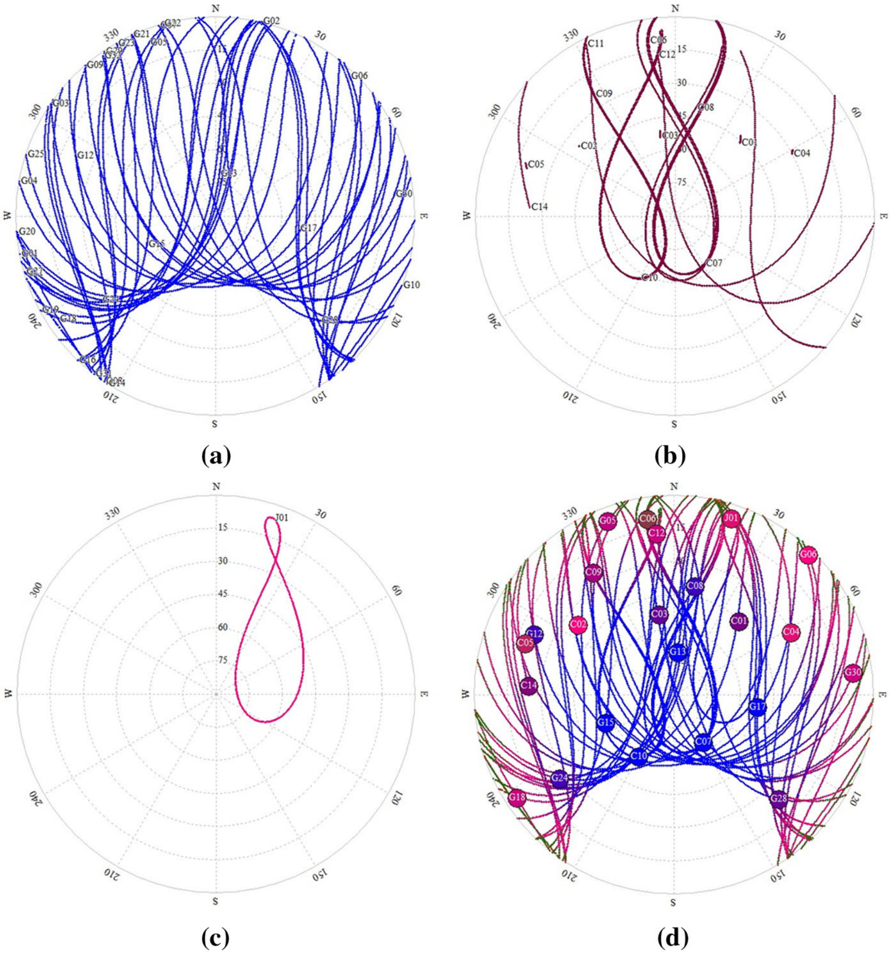

Fig. 3 Sky plots (azimuth vs. elevation) for the various satellite systems at station CUT0 on February 5, 2015: **a** GPS; **b** BDS; **c** QZSS; **d** GPS/BDS/QZSS

in vacuum. dt and dt_s are the satellite clock error and receiver clock error, respectively. I is the first-order ionospheric delay. T is the tropospheric delay. M_P and $M_{\boldsymbol{\Phi}}$ is the multipath error of the pseudorange, carrier phase measurements, ε_P and $\varepsilon_{\boldsymbol{\Phi}}$ are a combination noise of the pseudorange and carrier phase measurements.

In precise point positioning, the uncertainties in the satellite orbit and clock corrections can be significantly reduced by using precise GPS orbit and clock products. The other error sources including the satellite antenna phase centre offset, phase wind up, earth tide, ocean tide loading and atmosphere loading can be eliminated by correction model. The widely used ionosphere-free combination makes use of GPS radio frequency's dispersion property to mitigate the first order ionospheric delay effect. The observation model of ionosphere-free combination can be written (Abdel-salam 2005):

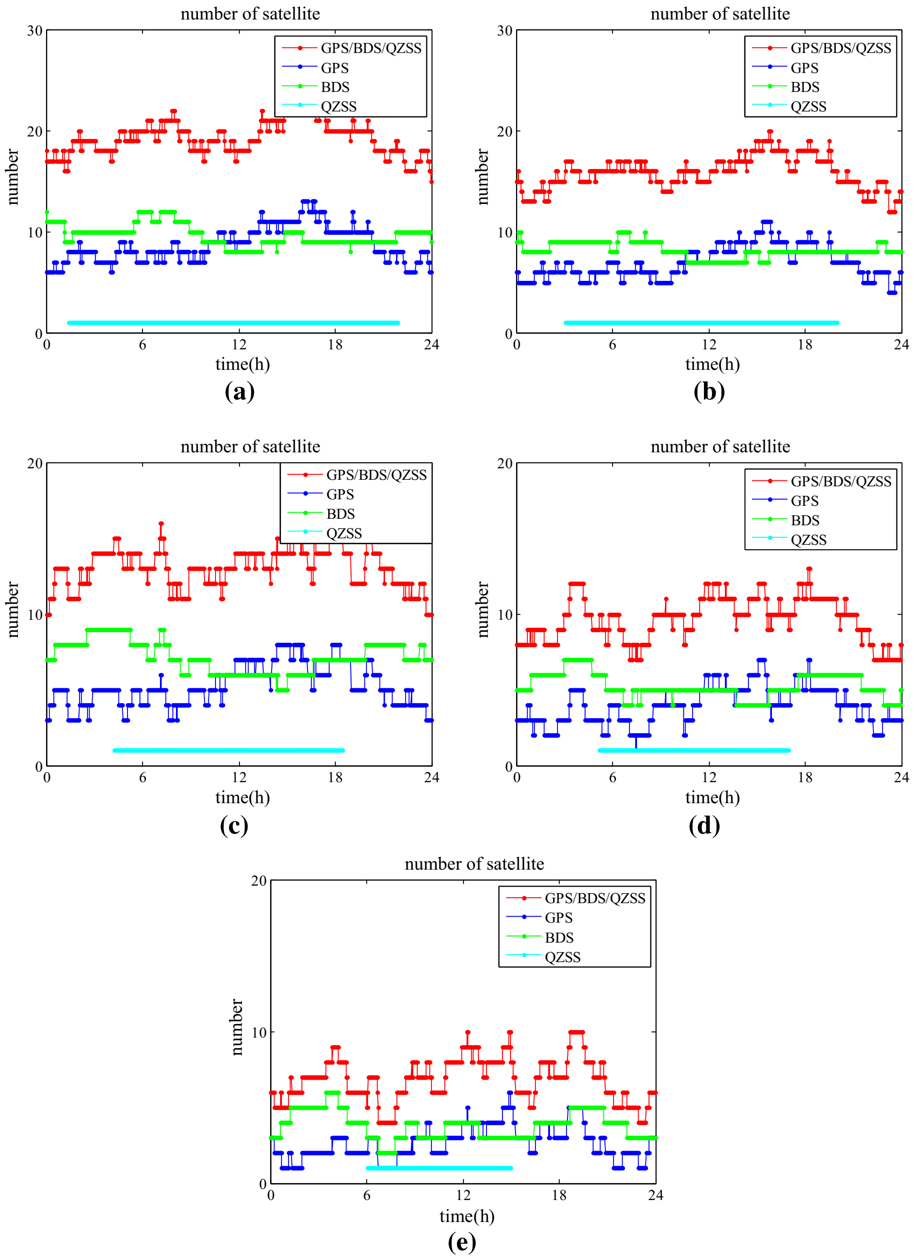

Fig. 4 The number of satellite for the various satellite systems under different cut-off elevation angles at station CUT0 on February 5, 2015: **a** 10°; **b** 20°; **c** 30°; **d** 40°; **e** 50°

$$P_{if} = \frac{f_1^2}{f_1^2 - f_2^2} P_1 - \frac{f_2^2}{f_1^2 - f_2^2} P_2 = \rho + c \times (dt - dt_s) + T + M_P + \varepsilon_P \tag{3}$$

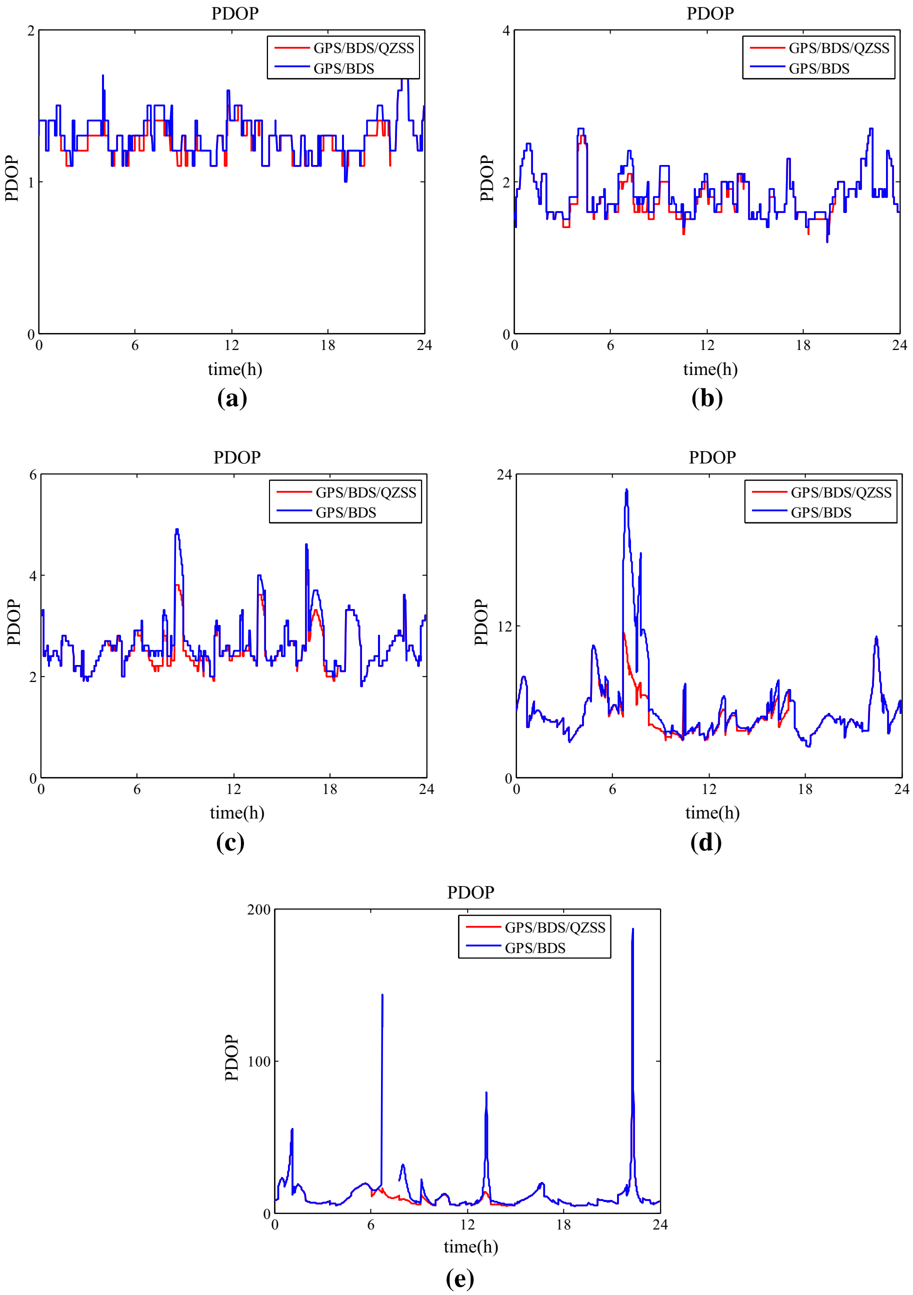

Fig. 5 PDOP value under different cut-off elevation angles at station CUT0 on February 5, 2015: **a** 10°; **b** 20°; **c** 30°; **d** 40°; **e** 50°

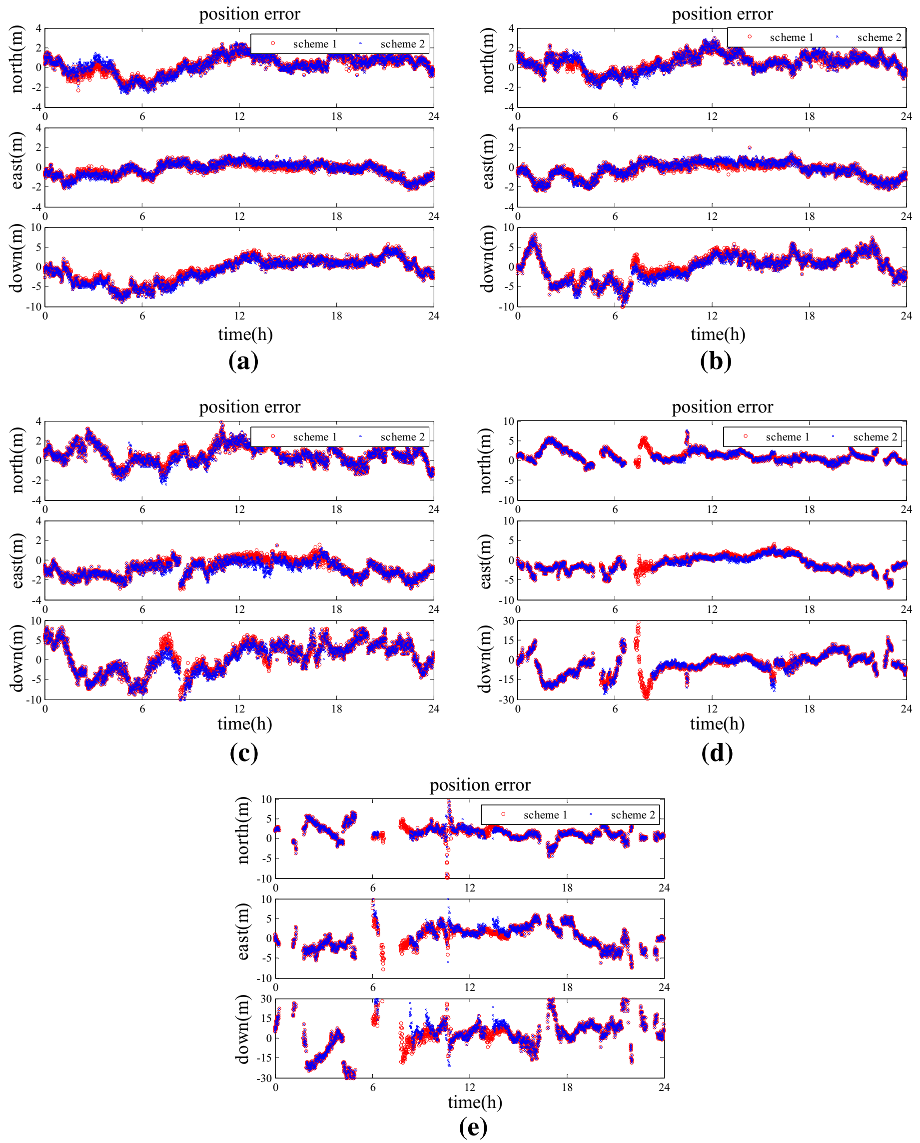

Fig. 6 SPP resolution of GPS/BDS system and GPS/BDS/QZSS system under different cut-off elevation angles at station CUT0 on February 5, 2015: **a** 10°; **b** 20°; **c** 30°; **d** 40°; **e** 50°

$$\boldsymbol{\Phi}_{if} = \frac{f_1^2}{f_1^2 - f_2^2}\boldsymbol{\Phi}_1 - \frac{f_2^2}{f_1^2 - f_2^2}\boldsymbol{\Phi}_2 = \rho + c \times (dt - dt_s) + T + \lambda_{if}N_{if} + M_{\boldsymbol{\Phi}} + \varepsilon_{\boldsymbol{\Phi}} \qquad (4)$$

where the subscript *if* is the ionosphere-free combination observation.

In order to test the improving availability and accuracy of GPS/BDS positioning using QZSS for single receiver, GPS, BDS and QZSS observation are process by single point positioning, static precise point positioning and kinematic precise point positioning, respectively. In single point positioning, only pseudorange is used (Li et al. 2014). Both

Table 2 The RMS and MAX values of SPP solution position error of GPS/BDS system and GPS/BDS/QZSS system in north, east and down components

Cut-off elevation angle	10° (m)		20° (m)		30° (m)		40° (m)		50° (m)	
	RMS	MAX	RMS	MAX	RMS	MAX	RMS	MAX	RMS	MAX
GPS/BDS/QZSS										
North	0.97	2.52	0.95	2.94	1.08	3.89	1.74	7.18	2.36	20.69
East	0.71	2.31	0.84	2.42	1.14	2.92	1.95	6.96	2.61	10.49
Down	3.02	8.82	3.10	9.68	3.93	12.43	7.85	22.38	12.91	41.36
GPS/BDS										
North	1.02	2.62	1.00	3.04	1.11	3.90	1.85	7.63	7.62	30.57
East	0.74	2.31	0.87	2.42	1.16	2.99	2.03	6.96	3.42	19.64
Down	3.19	9.06	3.19	9.87	3.98	13.33	8.67	25.92	21.50	56.33

Table 3 The success rate of SPP solutions of GPS/BDS system and GPS/BDS/QZSS system

Cut-off elevation angle	10° (%)	20° (%)	30° (%)	40° (%)	50° (%)
GPS/BDS/QZSS	100	100	100	92.9	79.5
GPS/BDS	100	100	100	88.2	72.9

pseudorange and carrier phase are used in static and kinematic precise point positioning. In kinematic precise point positioning, single point positioning resolution provides initial position to kinematic precise point positioning every epoch (Liu et al. 2015). The detailed resolution modes are shown in Fig. 2.

4 Data analysis

GNSS measurements recorded in 30-second intervals from IGS station CUT0 (Trimble NETR9 receiver) collected on February 5, 2015 are used in this study. The station CUT0 is located in Curtin, Australia. The final GNSS satellite orbits and clock products and the differential code biases produced by Center for Orbit Determination in Europe (CODE) are used. We also apply the absolute antenna phase center model and the phase windup corrections. The true coordinate benchmarks are from IGS weekly solution. The GPS/BDS/QZSS observation was processed by SPP, static PPP and kinematic PPP mode, respectively. Figure 3a, b and c show the sky plots (azimuth vs. elevation) of GPS, BDS and QZSS at station CUT0, respectively. The number of satellite for the various satellite systems under different cut-off elevation angles on that day are also calculated and shown in Fig. 4. Figure 5 shows the comparison of PDOP value under different cut-off elevation angles between GPS/BDS and GPS/BDS/QZSS. The PDOP value of three navigation system is less than that of GPS/BDS, especially under the cut-off elevation angles of 40° and 50°.

4.1 Single point positioning

The legend of scheme 1 represents single point positioning method with GPS/BDS/QZSS and the legend of scheme 2 represents single point positioning method with GPS/BDS.

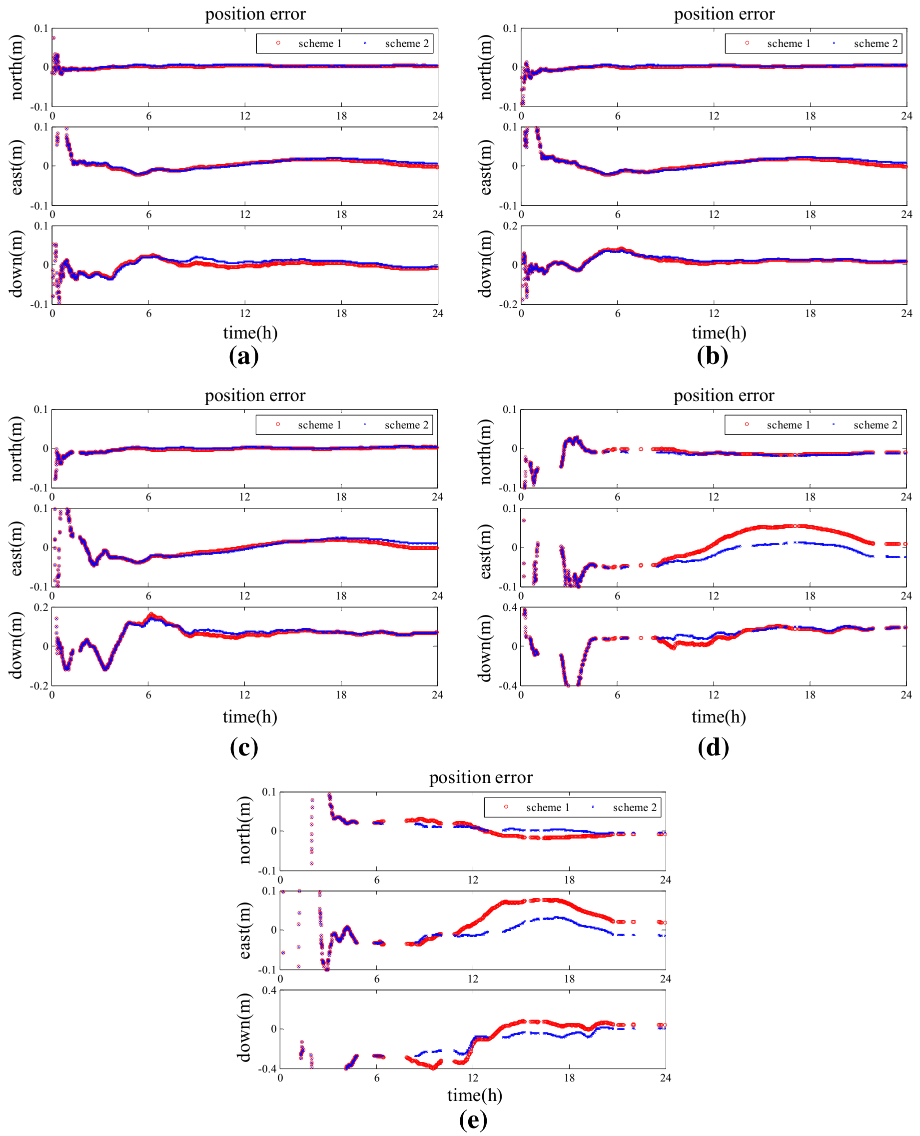

Fig. 7 Static PPP resolution of GPS/BDS system and GPS/BDS/QZSS system under different cut-off elevation angles at station CUT0 on February 5, 2015: **a** 10°; **b** 20°; **c** 30°; **d** 40°; **e** 50°

Position errors were computed with respect to the reference position to evaluate the performance. Figure 6 shows the time series of position errors in the north, east and down directions for scheme 1 and scheme 2. Table 2 illustrates root mean square errors (RMS) and maximum (MAX) value of position error. The success rate of SPP solutions of GPS/BDS/QZSS system and GPS/BDS system is summarized in Table 3. Compared to scheme 2, scheme 1 reduces all the errors of position error in the north, east and down directions. When cut-off elevation angle is 50°, the position of scheme 2 can achieve an

Table 4 The RMS and MAX values of static PPP solution position error of GPS/BDS system and GPS/BDS/QZSS system in north, east and down components

Cut-off elevation angle	10° (m)		20° (m)		30° (m)		40° (m)		50° (m)	
	RMS	MAX	RMS	MAX	RMS	MAX	RMS	MAX	RMS	MAX
GPS/BDS/QZSS										
North	0.003	0.006	0.003	0.004	0.003	0.007	0.012	0.016	0.036	0.070
East	0.006	0.021	0.012	0.022	0.018	0.039	0.016	0.037	0.056	0.093
Down	0.010	0.036	0.029	0.073	0.079	0.146	0.150	0.205	0.272	0.511
GPS/BDS										
North	0.004	0.007	0.004	0.005	0.004	0.007	0.014	0.018	0.065	0.096
East	0.008	0.023	0.014	0.023	0.020	0.039	0.036	0.054	0.083	0.102
Down	0.013	0.038	0.031	0.084	0.083	0.163	0.162	0.207	0.336	0.518

Table 5 The success rate of static PPP solutions of GPS/BDS system and GPS/BDS/QZSS system

Cut-off elevation angle	10° (%)	20° (%)	30° (%)	40° (%)	50° (%)
GPS/BDS/QZSS	100	100	98.2	74.8	68.2
GPS/BDS	100	100	97.2	66.4	57.2

accuracy of 2.36, 2.61 and 12.91 m in the north, east and down coordinate components, respectively. The success rate of SPP solutions of GPS/BDS system is improved from 88.2 to 92.9 % using QZSS under 40° cut-off elevation angle. At 50° elevation cutoff, the QZSS improves the success rate of SPP solutions of GPS/BDS system from 72.9 to 79.5 %.

4.2 Static precise point positioning

The legend of scheme 1 represents static precise point positioning (PPP) method with GPS/BDS/QZSS and the legend of scheme 2 represents static PPP method with GPS/BDS. Position errors were computed with respect to the reference position to evaluate the performance. Figure 7 shows the time series of position errors in the north, east and down directions for scheme 1 and scheme 2. Table 4 illustrates root mean square errors (RMS) and maximum (MAX) value of position error. The success rate of static PPP solutions of GPS/BDS/QZSS system and GPS/BDS system is summarized in Table 5. The same as SPP, compared to scheme 2, scheme 1 reduces all the errors of position error in the north, east and down directions. Compared with the scheme 2, the position accuracies in the north, east and down directions are improved by 44, 33 and 19 % for the scheme 1 under 50° cut-off elevation angle, respectively. The success rate of static PPP solutions from GPS/BDS system is improved from 57.2 to 68.2 % using QZSS under 50° cut-off elevation angle.

4.3 Kinematic precise point positioning

The legend of scheme 1 represents kinematic precise point positioning (PPP) method with GPS/BDS/QZSS and the legend of scheme 2 represents kinematic PPP method with GPS/BDS. Position errors were computed with respect to the reference position to evaluate the

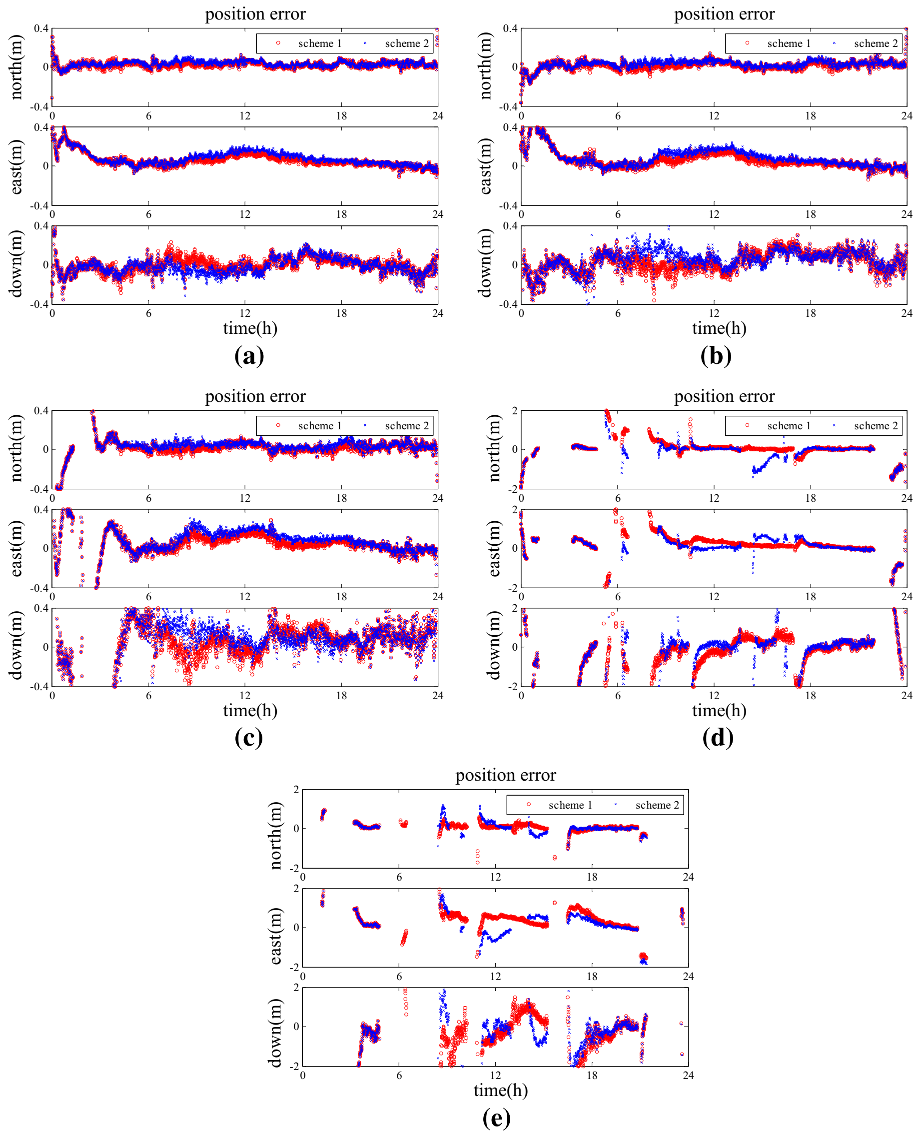

Fig. 8 Kinematic PPP resolution of GPS/BDS system and GPS/BDS/QZSS system under different cut-off elevation angles at station CUT0 on February 5, 2015: **a** 10°; **b** 20°; **c** 30°; **d** 40°; **e** 50°

performance. Figure 8 shows the time series of position errors in the north, east and down directions for scheme 1 and scheme 2. Table 6 illustrates root mean square errors (RMS) and maximum (MAX) value of position error. The success rate of static PPP solutions of GPS/BDS/QZSS system and GPS/BDS system is summarized in Table 7. Compared with the scheme 2, the position accuracies in the north, east and down directions are improved by 29, 33 and 14 % for the scheme 1 under 30° cut-off elevation angle, respectively. The success rate of kinematic PPP solutions of GPS/BDS system is improved from 63.1 to

Table 6 The RMS and MAX values of kinematic PPP solution position error of GPS/BDS system and GPS/BDS/QZSS system in north, east and down components

Cut-off elevation angle	10° (m)		20° (m)		30° (m)		40° (m)		50° (m)	
	RMS	MAX	RMS	MAX	RMS	MAX	RMS	MAX	RMS	MAX
GPS/BDS/QZSS										
North	0.036	0.125	0.036	0.138	0.037	0.133	0.312	1.416	0.631	2.675
East	0.073	0.232	0.072	0.185	0.089	0.286	0.353	0.672	0.589	1.457
Down	0.066	0.286	0.114	0.363	0.160	0.554	0.860	3.864	1.369	4.946
GPS/BDS										
North	0.044	0.129	0.047	0.140	0.052	0.153	0.451	1.536	0.845	3.673
East	0.095	0.232	0.102	0.238	0.133	0.302	0.416	1.228	0.966	2.962
Down	0.073	0.311	0.102	0.402	0.185	0.734	0.895	4.904	1.762	6.326

Table 7 The success rate of kinematic PPP solutions of GPS/BDS system and GPS/BDS/QZSS system

Cut-off elevation angle	10° (%)	20° (%)	30° (%)	40° (%)	50° (%)
GPS/BDS/QZSS	100	100	98.2	68.0	52.7
GPS/BDS	100	100	98.1	63.1	43.2

68.0 % using QZSS under 40° cut-off elevation angle. The success rate of kinematic PPP solutions of GPS/BDS system enhanced by QZSS is increased from 43.2 % to 52.7 % with 50° elevation cutoff.

5 Conclusion

This paper presents GPS/BDS positioning using QZSS for single receiver. Through the analysis and comparison for the resolution error between GPS/BDS positioning and GPS/BDS/QZSS positioning, the availability and accuracy of GPS/BDS positioning are improved with QZSS for single point positioning mode, static precise point positioning mode and kinematic precise point positioning mode. The QZSS is also able to increase the resolution success rate, especially in the period with high cut-off elevation angle. Compared with the GPS/BDS, the three-dimensional position accuracies of three resolution modes are improved by about 9 % for the GPS/BDS/QZSS under 40° cut-off elevation angle. The horizontal position from GPS/BDS/QZSS can achieve accuracy levels of 3.52, 0.067 and 0.863 m for three resolution modes under 50° cut-off elevation angle, respectively. When compared to GPS/BDS, the GPS/BDS/QZSS improves the horizontal position accuracies by 58, 37 and 33 %, respectively. The success rate of SPP solutions from GPS/BDS system is improved from 72.9 to 79.5 %, the success rate of static PPP solutions from GPS/BDS system is improved from 57.2 to 68.2 % and the success rate of kinematic PPP solutions from GPS/BDS system is improved from 43.2 to 52.7 % using QZSS under 50° cut-off elevation angle. The success rate of GPS/BDS positioning is increased almost 10 % with QZSS for single point positioning mode, static precise point positioning mode and kinematic precise point positioning mode under the cut-off elevation angles of 40° and 50°.

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