

Chapter 40

Assessment of BDS Signal-in-Space Accuracy and Standard Positioning Performance During 2013 and 2014

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Abstract At the end of 2011, BeiDou Satellite Navigation System (BDS) moved into the phase of experimental operation, indicating that BDS, after GPS and GLONASS, became the third satellite system providing free service of PNT. In this paper, the positioning performance of BDS from Jan, 2013 was assessed. The data sources, as well as the generation of precise orbit and clock, were described, and the precisions of broadcast orbit, clock and signal in space for GEO/IGSO/MEO satellites were analyzed. The civil signal B1I of BDS was utilized to assess the accuracy of single point positioning (SPP) with code measurements. It is illustrated that the precision of URE for BDS could reach 1.5–2.0 m, and that the both horizontal and vertical precision of SPP reach 10 m in service area.

Keywords BeiDou · Broadcast ephemeris · Signal-in-space · URE · SPP · Performance assessment

40.1 Introduction

Based on the success of BeiDou I experimental satellite system, the building of Beidou II was kicked off in 2004, and the first medium-earth-orbit (MEO) satellite was launched 3 years later. In 2011, three satellites in the geostationary orbit (GEO)

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and four in the inclined geosynchronous orbits (IGSO) were properly deployed, possessing the capacity of regional navigation and positioning. At the end of 2011, the initial operation of BeiDou (BDS) regional satellite system was announced officially. Up to the end of the year 2012, five GEO satellites, five IGSO and four MEO ones had been deployed, and BDS began to formally provide positioning, navigation and timing (PNT) service in Asia-Pacific area. In June, 2014, BDS had been operating for 18 months, and the information of its constellation is shown in Table 40.1.

The performance of signal in space is one of the critical factors in positioning precision and integrity monitoring of GNSS [1]. Signal in space range error (SISRE) or user range error (URE) is the difference between the real position and clock of the satellites and their values in predicted ephemeris, reflecting the precision of ephemeris and finally affecting the positioning accuracy for real-time user. In this paper, the performance of SISRE and positioning of BDS during Jan, 2013 and Jun, 2014 was assessed. Firstly, the method of determining the assessment standards, i.e. the precise orbit and clock products, was described, and SISRE equations tailored to BDS was proposed. The performance of SISRE and PNT service for BDS was then analyzed.

Table 40.1 The components and specifications of satellites for BDS regional constellation

Orbit types	Satellite name (PRN)	Launch date	Altitude (km)	Inclination (°)	Longitude (°)	Status
GEO	G01(C01)	2010.01.17	35,786	<1	140.00E	Normal
	G02	2009.04.14	35,786	–	–	Inactive
	G03(C03)	2010.02.06	35,786	<1	110.50E	Normal
	G04(C04)	2010.11.01	35,786	<1	160.00E	Normal
	G05(C05)	2012.02.24	35,786	<1	58.75E	Normal
	G06(C02)	2012.10.25	35,786	<1	80.00E	Normal
IGSO	I01(C06)	2010.01.08	35,786	55	101–136E	Normal
	I02(C07)	2010.12.18	35,786	55		Normal
	I03(C08)	2011.04.10	35,786	55		Normal
	I04(C09)	2011.07.26	35,786	55	79–112E	Normal
	I05(C10)	2011.12.02	35,786	55		Normal
MEO	M03(C11)	2012.04.29	21,528	55	–180 to 180E	Normal
	M04(C12)	2012.04.29	21,528	55		Normal
	M05(C13)	2012.09.18	21,528	55		Unavailable since Jan, 2014
	M06(C14)	2012.09.18	21,528	55		Normal

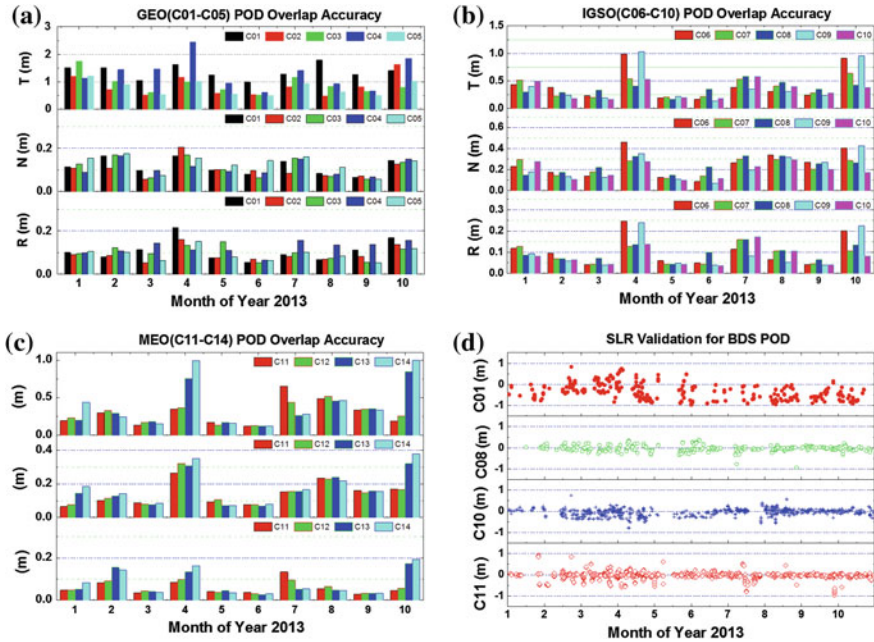


Fig. 40.2 Difference of GEO/IGSO/MEO precise solutions (Jan–Oct, 2013)

In order to assess precision of orbit, the overlap of the first and third arcs of three successive arcs are compared. Shown in Fig. 40.2a–c is the average precision of GEO/IGSO/MEO satellites, respectively, during Jan and Oct in 2013. The precision of GEO satellites in along-track (A), cross-track (C) and radial (R) direction is 1.00, 0.12 and 0.10 m, respectively. Those for IGSO satellites are 0.36, 0.21 and 0.09 m, while MEO 0.33, 0.15 and 0.07 m, respectively. The above results show that the along-track precision of G01 is the worst, which can be explained by its weak geometry and the uneven distribution of stations [4]. It is worth noting that the radial precision, which affects positioning the most, for all three types of satellites are better than 10 cm.

The precision of orbit could also be verified by SLR observables through the external consistency. G01 and I03 and M03 are all equipped with laser reflecting prisms, and the SLR checking results for the three satellites are 0.24, 0.12 and 0.12 m, respectively. Shown in Table 40.2 are the internal and external consistencies for all three satellites.

The above precise orbit with precision better than 10 cm in radial direction, as well as the corresponding clock, is taken as the “real value references”.

Table 40.2 Average precision of BDS precise orbit (Jan–Oct, 2013)

Satellite type	Overlap precision (m)			SLR check (m)
	A	C	R	
GEO	1.00	0.12	0.10	0.24
IGSO	0.36	0.21	0.09	0.12
MEO	0.33	0.15	0.07	0.09

40.3 Method of Assessment

40.3.1 Preprocessing

Station navigation ephemeris files of BETS network are merged into one file which contains all satellites ephemeris information, some error data caused by receiver (e.g. failure decoding) are removed [5]. On the other hand, navigation satellites with orbit maneuver and/or integrity alert information are excluded [6], and the health flag in navigation ephemeris is used to decide whether a satellite is usable or not [7]. Since the master control stations of BDS are in native region, the GEO and IGSO satellites will be tracked in most of the time, the corresponding satellites navigation information can be updated conveniently and in time (every 1 h). The AOD (age of data) of these satellites’ ephemeris is 1 h, shorter than that of GPS. The case is different for MEO satellites, which only can be tracked for a short time in 1 day, so the MEO satellites ephemeris with a relative longer AOD with a not perfect prediction position accuracy. In this paper, only the ephemeris with AOD smaller than 1 h is employed in statistics. Considering that the BDS constellations are still in construction, some satellites are unavailable. Overall, the availability rate of data from GEO and IGSO satellites is over 90 %, while the MEO satellites usable ephemeris is only 70–80 %. Finally, the data with difference between precise orbit and broadcast ephemeris larger than 50 m are excluded in statistics and this assumption is reasonable, considering that 50 m is larger than 30 times of standard deviation for signal in space range error.

40.3.2 Comparison Between Precise and Predicted Orbit

As mentioned above, the precise orbit accuracy of BDS is between 10 and 50 cm, much better than the broadcast ephemeris, so it is taken as reference value and the difference between precise orbit and broadcast ephemeris is considered the broadcast satellites position error. Meanwhile, noting that the precise orbit and broadcast one is not in the same reference frame, the reference frame must be unified before comparison. The computation of BDS precise orbit is under ITRF2008, while the broadcast ephemeris is under CGCS2000 (China Geodetic Coordinate System 2000). Theoretically, position under CGCS2000 should converse to ITRF2008 by seven transformation parameters (three for translation, three

for rotation, and one for scale) [8]. Given that the difference between CGCS2000 and ITRF1997 or ITRF2008 is only several centimeters [9, 10], the transformation between CGCS2000 and ITRF2008 is not considered in this paper.

40.3.3 Comparison Between Precise and Predicted Clocks

When determining the satellite orbit, the satellite relative clock is computed by a selected reference clock, and the selected reference clock can be either a receiver clock or a satellite clock. The different reference clock used has no impact on the user navigation and positioning as the bias existing in the same satellite clock can be absorbed in receiver clock estimation. The BDT is maintained by military time-frequency equipment, while the independent receiver clock is used for orbit determination. Under this condition, a method with second-order differencing is used for broadcast clock assessment instead of first-order differencing. What is more, the predicted clock bias of BDS is based on frequency B3I, so the TGD (group delay timing) correction in broadcast ephemeris between B1I and B3I should be taken into account when assessing the satellite predicted clock bias on B1I. The satellite predicted clock error can be computed by the below formula:

$$\Delta t^i = dt^i - \mu \quad (40.1)$$

where, $dt^i = T^i - t^i$ is the first-order difference between precise satellite clock bias and broadcast clock bias, $\mu = \sum_{i=1}^n dt^i/n$ is the mean of all satellites and used as the datum difference between precise and broadcast satellite clock.

40.3.4 Calculation of URE for BDS

According to ref. [11], if a receiver with known position is synchronized to navigation system time, then the expectation of the difference between pseudo range (the range between satellite position broadcast by satellites and receiver location) and measured range by receiver is IURE (Instantaneous User Range Error). IURE only consists of ephemeris error caused by space and control Segments, ranging error caused by user segment (e.g. troposphere delay, multipath error and noise) is not included in IURE. The main error for IURE comes from prediction satellites position error and satellites clock error. IURE is a function of time and space. In practical statistics, the RMS (root mean square) of IURE is considered the precision of IURE [12]. There are some differences about RMS URE computation between GPS and BDS:

- BDS include three different kinds of satellites, i.e. MEO, IGSO and GEO satellites. Generally, the higher the orbit altitude is, the larger the impact of satellite radial direction position error on user ranging error is [7]. The projection factor for MEO is 0.98 and 0.99 for IGSO/GEO, while the impacts of cross and normal direction position error are much smaller, i.e. 0.0078 and 0.0204 for the cross position projection and the normal position projection, respectively. This means the satellite position error in cross and normal direction is less than 1/11 of radial direction. For MEO satellites, the position error projection factor is 0.98 and 0.0185 in radial direction and cross/normal direction, respectively.
- Noting the property of GEO/IGSO satellites, the coverage region area is different from MEO satellites, so the RMS of IURE for IGSO/GEO is regional other than global level.
- Satellites position error and clock error is correlative [11]. Results from GPS SPS show that the satellite radial direction position error has significant negative correlation and the coefficient is -1.0 . GPS satellites position and clock error are computed by pseudo-range measurements. BDS satellites position is predicted by the same way, while the satellites clock is obtained through time-two-way comparison method. The correlation coefficient is smaller than GPS, RMS of IURE is computed as

$$rms\ URE_{BDS(GEO,IGSO)} = \sqrt{(0.99R)^2 + T^2 + \frac{1}{127}(A^2 + C^2)} \quad (40.2)$$

$$rms\ URE_{BDS(MEO)} = \sqrt{(0.98R)^2 + T^2 + \frac{1}{54}(A^2 + C^2)} \quad (40.3)$$

40.4 Assessment Results and Analysis

With the above-mentioned method, the SISRE, ionosphere model and positioning accuracy of BDS during Jan, 2013 and Jun, 2014 were assessed.

40.4.1 Precision of Broadcast Orbit

Shown in Fig. 40.3a–c are the results for GEO (C01-C05), IGSO (C06-C10) and MEO (C11-C14) satellites, and the “mean” in each panel references the average of all 14 satellites. Comparing among the three types of satellites, it can be found that the radial precision of GEO satellites are marginally higher than the average precisions of GEO/IGSO/MEO satellites and the precisions of GEO satellites are more or less the same. The radial precision for C02 is the best, while the along-track

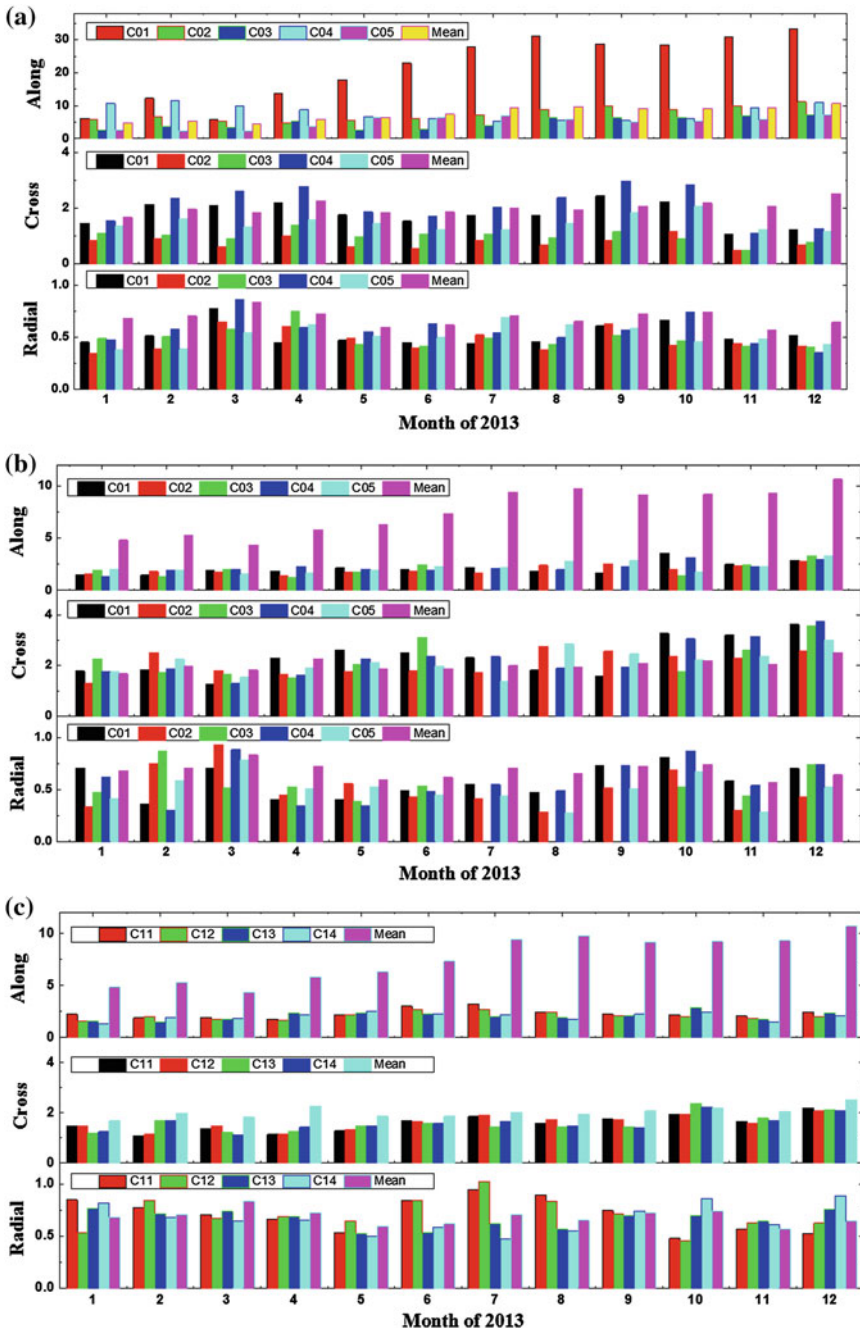


Fig. 40.3 Precision of broadcast orbit for BDS satellites (Jan, 2013–Jun, 2014). **a** Precision of broadcast orbit for GEO satellites (2013). **b** Precision of broadcast orbit for IGSO satellites (2013). **c** Precision of broadcast orbit for MEO satellites (2013). **d** Precision of broadcast orbit for GEO satellites (2014). **e** Precision of broadcast orbit for IGSO satellites (2014). **f** Precision of broadcast orbit for MEO satellites (2014)

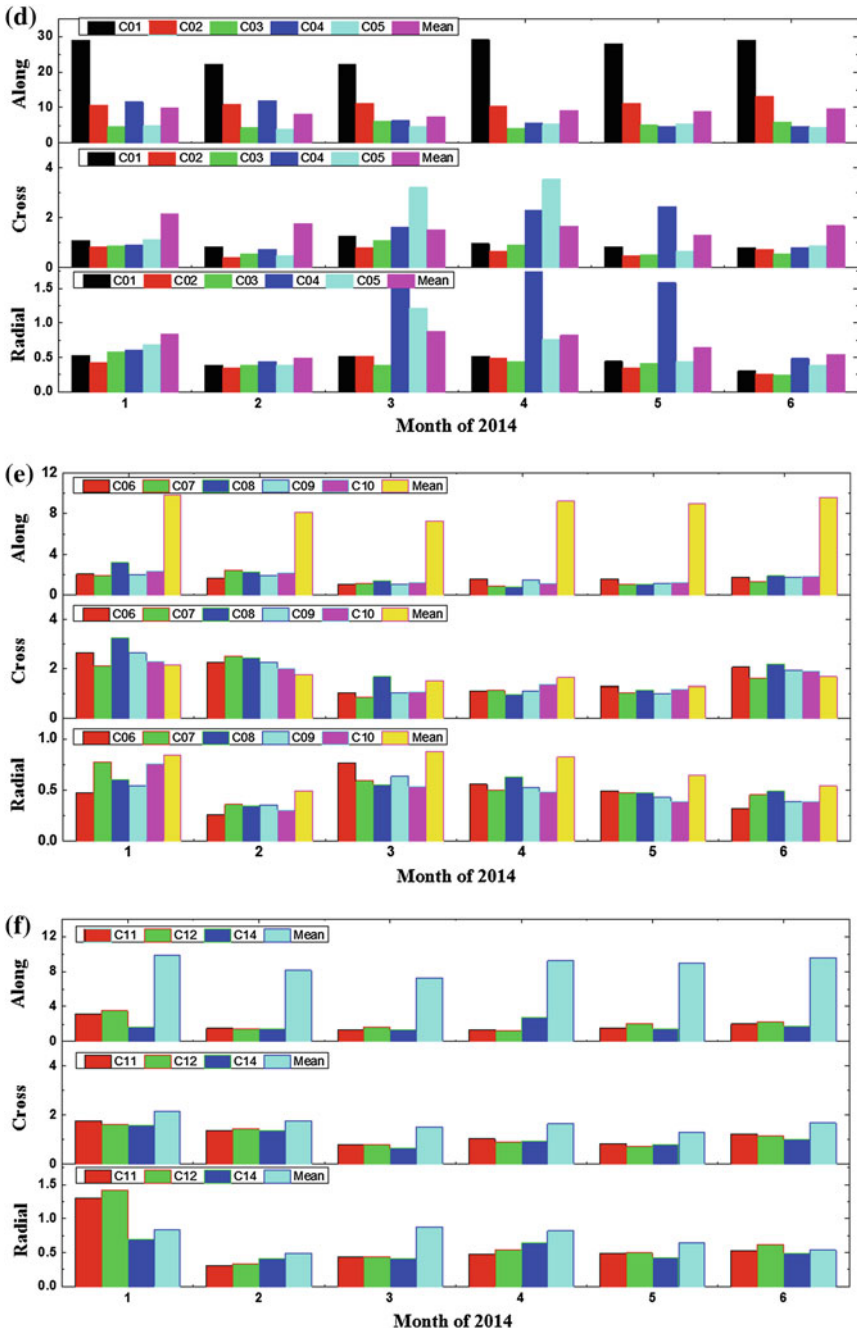


Fig. 40.3 (continued)

precision for C01 the worst. The radial precisions for most satellites could reach 0.5–0.8 m, and the cross-track precisions are better than 2.0 m. The along-track precisions are significantly different from satellite to satellite. Those for most GEO satellites are greater than 5.0 m. The along-track precision for C01 even reaches 10–20 m, while those for IGSO and MEO satellites are about 2.0–3.0 m.

Compared with the year 2013, the BDS broadcast ephemeris in 2014 shows the equivalent precision in along-track direction, but shows better precisions in cross-track and radial direction. The along-track precisions of GEO satellites keep stable in the 2 years, the precisions of IGSO satellites slightly improve in all three directions. The radial precisions of MEO satellites stay at around 0.5 m, and the along-track and cross track 1.5–2.0 m.

40.4.2 Precision of Broadcast Clocks

Normally, the broadcast ephemeris for GEO and IGSO satellites are updated every hour. Frequently updating could help improve the precision of predicted orbit and clocks. Shown in Fig. 40.4a, b are the standard deviations of differences between broadcast and precise clocks for BDS satellites during 2013 and 2014, most of which fall between 2 and 6 ns. In 2013, the clocks of BDS satellites are relatively stable. The precisions of broadcast clocks of GEO satellites are 4–8 ns, slightly worse than those of IGSO and MEO satellites. The precisions for IGSO satellites are around 2–3 ns. Since the ages of assessment data for MEO satellites are longer than 1 h, their precision are around 4 ns, marginally inferior to those of IGSO satellites.

The broadcast clocks of 2014 are around 4 ns, generally consistent with those of 2013. However, the precisions of most GEO and IGSO satellites improve by 1 ns, and they are stable from month to month. The precision of broadcast clocks for MEO satellites are 3–5 ns, consistent with those of 2013.

40.4.3 Signals-in-Space Precision

The calculation of SISRE for BDS satellite is not only different from GPS satellite, but also different for different types of BDS satellites, due to the orbit altitudes. With the tailored equations, the SISREs of BDS satellites during 2013 and 2014 are analyzed, and the results are shown in Fig. 40.5.

Generally speaking, the monthly average UREs of all BDS satellites are relatively stable in 2013, falling between 1.5 and 2.0 m, as shown in Fig. 40.5a. The standard deviation of URE GEO satellites is the greatest, which is mainly caused by the weak geometry and sparse stations. The along-track precision for GEO satellites as C01 and C04 could reach several or even tens of meters, and the precision of clocks are also affected. The precisions of IGSO satellites (C06–C10), with better

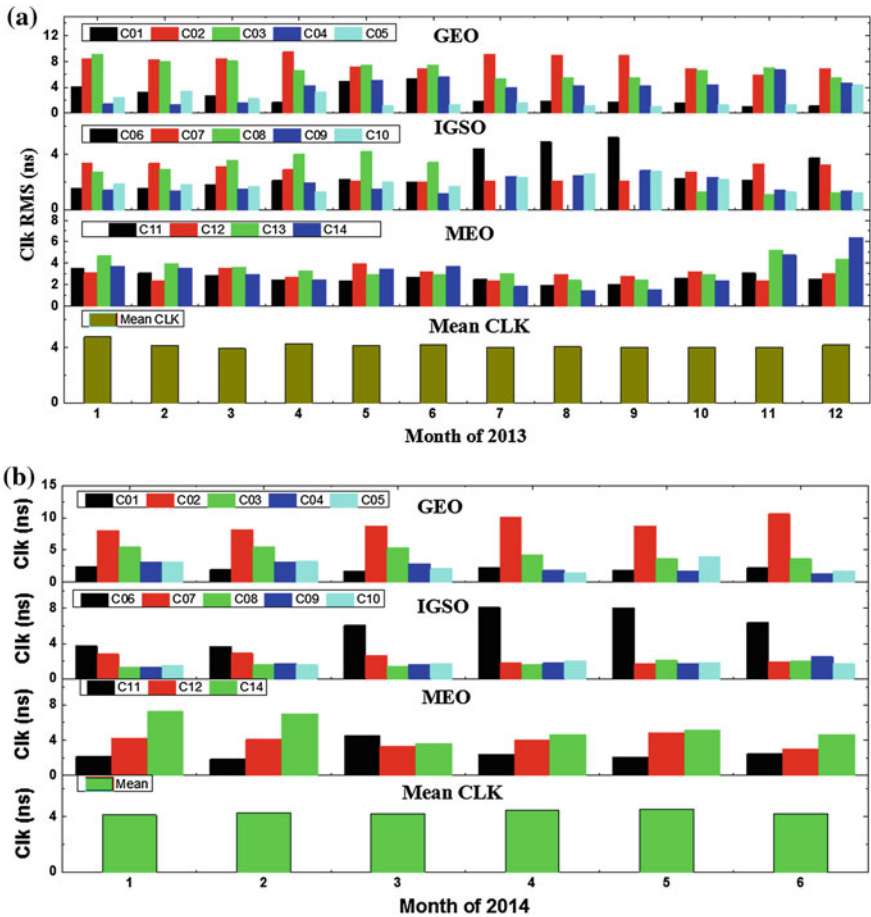


Fig. 40.4 Statistical results of broadcast clocks precisions for BDS satellites (Jan, 2013–Jun, 2014). **a** Broadcast clocks for BDS satellites in 2013. **b** Broadcast clocks for BDS satellites in 2014

geometry, could stay in 2–3 m in along-track and cross track directions, and less than 1 m in radial direction. In addition, the broadcast ephemeris of IGSO satellites update every hour, which helps reduce the extrapolating error and thus improve the URE precision indirectly. However, the MEO satellites are not as fortunate. Although they have equally good or even better observing geometry in Asia-Pacific area, they depend on the extrapolation when wandering outside this region. The longer they are extrapolated, the lower the precision will be. When the abroad part of MEO ephemeris is taken into account, the URE will definitely decrease. This is why the URE of MEO satellite is worse than IGSO satellite in Fig. 40.5. Anyway, the URE precision of MEO satellite, falling in 1.5–1.8 m, is better than GEO satellite.

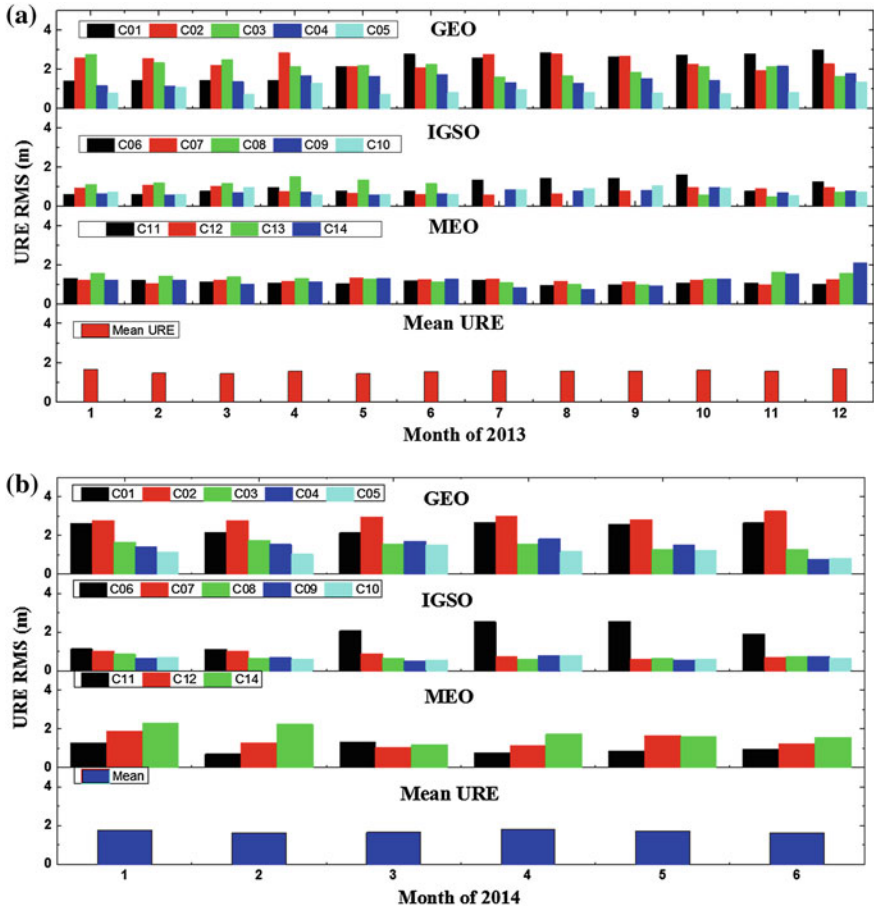


Fig. 40.5 URE precisions for BDS satellites (Jan, 2013–Jun, 2014). **a** URE precision for BDS satellites in 2013. **b** URE precision for BDS satellites in 2014

The general trends of URE in 2014 and 2013 are similar, with an average of 1.8 m. The URE precision of IGSO is the best and GEO the worst. The URE precisions for C02 and C06 are relatively low, due to their bad clocks. Glitches occurred with C13 in 2014, so their UREs are not analyzed here.

40.4.4 Analysis of Positioning Precision with BDS Pseudoranges

To investigate the influence of BDS constellation addition, the time period was divided into three phases, which is shown in Table 40.3. With the number of

Table 40.3 The composition of BDS constellation in different periods

No.	Constellation	Periods
1	3G+4I	2012.01.01–2012.02.06
2	3G+5I	2012.02.07–2012.04.15
3	4G+5I	2012.04.16–2012.06.29
4	4G+5I+2 M	2012.07.01–2012.10.31
5	5G+5I+4 M	2012.11.28–present

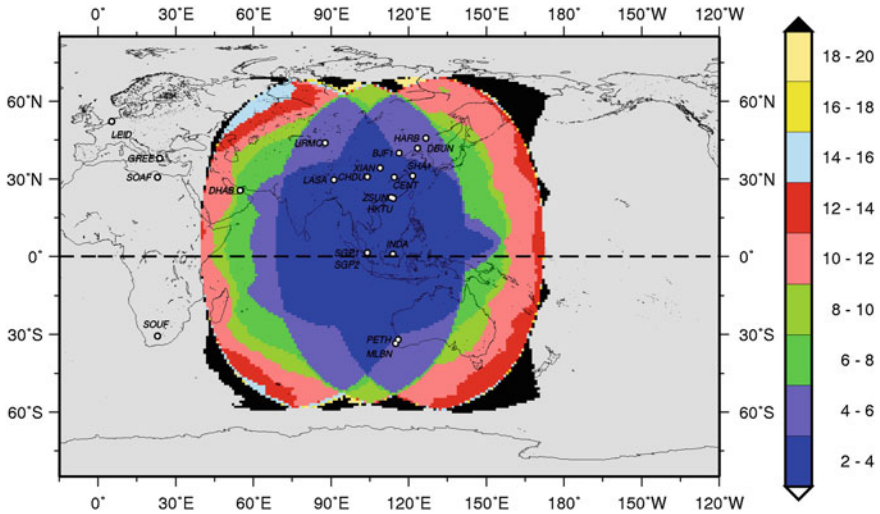


Fig. 40.6 Distribution of PDOP (95 %) for BDS (5GEO+5IGSO+4MEO)

satellites increasing in the year 2011 and 2012, the dilution of precision (DOP) was significantly improved between 75°E and 135°E (see Fig. 40.6), and the PDOP between 30°S and 30°N could reach 2–4 (95 %). When the coverage expanded to the whole Asia-Pacific area, the PDOP is still less than 8. Since the current 14 satellites include GEO, IGSO and MEO ones, the distribution of PDOP in Asia-Pacific area is not even. Three typical stations in the region are selected to analyze the precision of SPP, and the station information is shown in Table 40.4.

Shown in Figs. 40.7, 40.8, 40.9 and 40.10 are the results of SPP with B1I code measurements of BDS. The addition of BDS constellation is of great significance in

Table 40.4 Station information for SPP

Station ID	Observables types	Latitude	Longitude	Receiver types
BJF1	B2I	+40.0	116.3	UNICORE
CHDU	B1I	+30.7	+104.1	UNICORE
SIGP		+1.4	+103.9	UNICORE
PETH		-31.9	+115.8	UNICORE

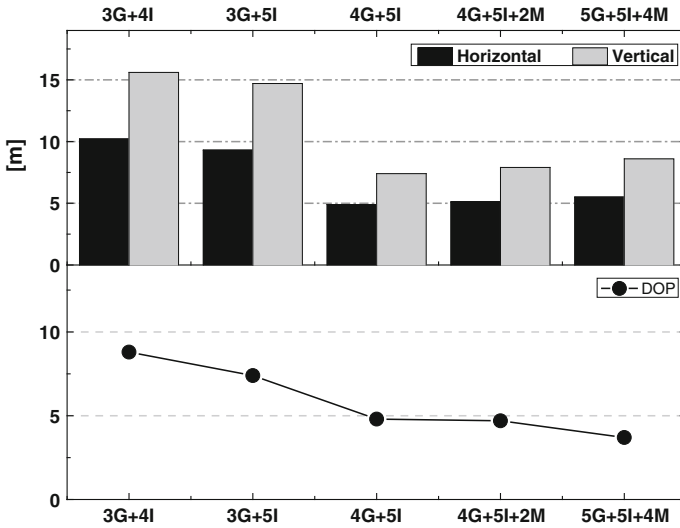


Fig. 40.7 Positioning precision for station BJF1

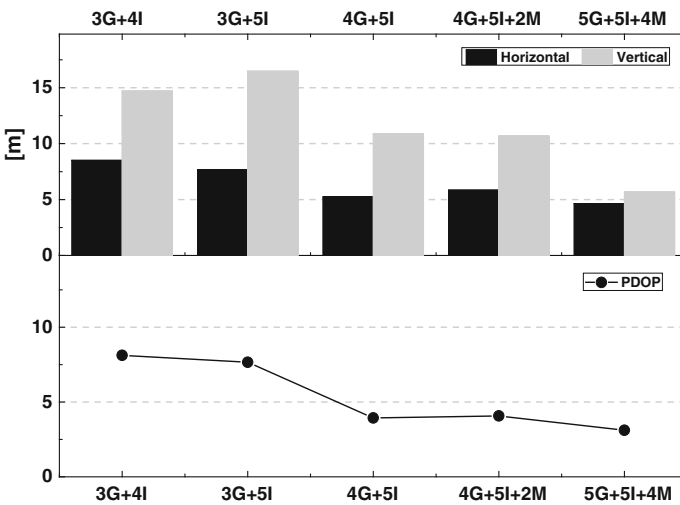


Fig. 40.8 Positioning precision for station CHDU

improving PDOP. When the constellation contained three GEO and five IGSO satellites, the PDOP at the above three stations are greater than 5. The precision of positioning (95 %) with BDS single frequency was about 10 m in horizontal and 15 m in vertical. After the fifth GEO satellite was added, the observing geometry improved significantly. The precision of positioning (95 %) with BDS single frequency was better than 5 m in horizontal and almost 10 m in vertical. When the

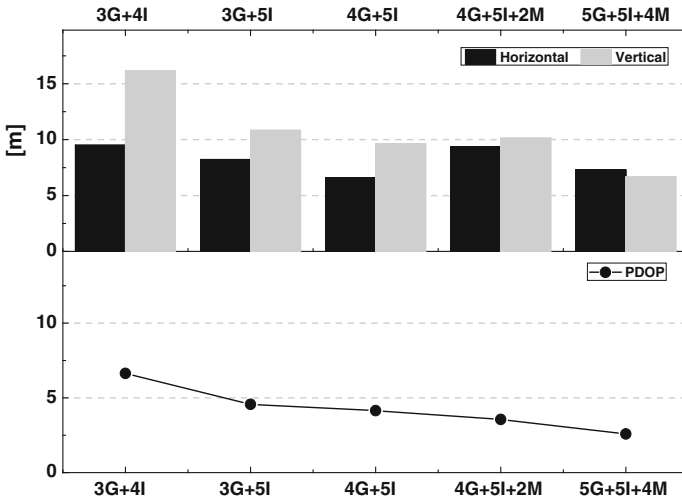


Fig. 40.9 Positioning precision for station SIGP

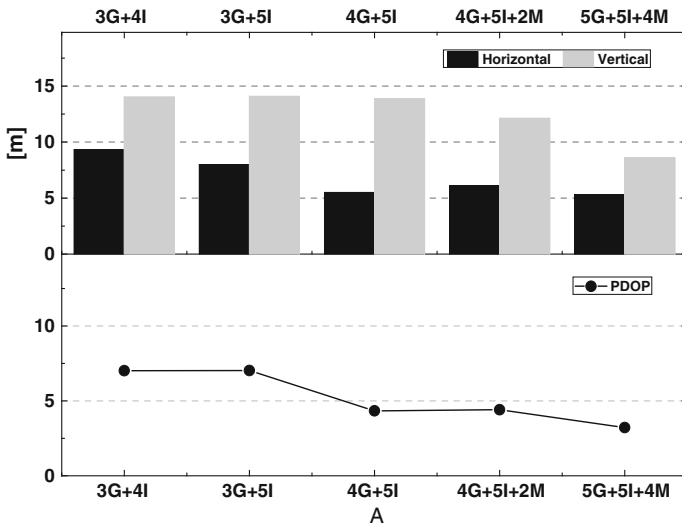


Fig. 40.10 Positioning precision for station PETH

first two MEO satellites were added, no significant improvement was seen in the observing geometry and positioning precision. After another two MEO satellites were added in Nov, 2012, the precision of SPP was improved significantly to better than 6 m (95 %) in horizontal and better than 10 m (95 %) in vertical. According the above results, the precision of SPP with BDS single-frequency measurements can reach 10 m both in horizontal and vertical.

40.5 Conclusions

Some conclusion can be obtained based on the above statistics for the signal in space error and navigation performance on civil frequency B1I:

- (1) There are some small differences among GEO, IGSO and MEO satellites prediction position error. Generally, the position precision is about 0.5–0.8 m for radial direction and better than 2.0 m in normal direction, while for cross direction, the GEO satellites is larger than 5 m in most cases, especially for G01 (the precision is about 10–20 m). The precision of IGSO and MEO satellite orbits is at the same level and the average RMS is about 2.0–3.0 m.
- (2) For BDS satellites broadcast clock error, the mean RMS value of all satellites is about 2–6 ns and the clock performance are stable in 2013. Some differences can be found in three different types of satellites: GEO satellites broadcast clock error is worse than IGSO and MEO satellites, with the RMS about 4–8 ns; it is about 2–3 ns for IGSO satellite; since some MEO broadcast ephemeris AOD are larger than 1 h, the precision of MEO satellites clock is at the level of 4 ns, not as good as IGSO.
- (3) The SISA (signal in space accuracy) of BDS GEO/IGSO/MEO is about 1.5–2.0 m. The same case holds for position and clock precision. The GEO satellites have the worst value, i.e. about 1.5–2.0 m, while it is 1.0 and 1.7 m for IGSO and MEO satellites, respectively.
- (4) With the optimization of BDS constellation structure, i.e. from 3 GEO and 4 IGSO satellites to 5 GEO, 5 IGSO and 4 MEO satellites, BDS navigation performance is improved significantly. The horizontal positioning accuracy (95 %) is improved from 10 to 6 m, and 15–10 m for vertical direction. The navigation results of typical stations in service region show that BDS can provide 10 m navigation service in both horizontal and vertical direction in Asia region.

Acknowledgments This work was partially sponsored by Special Foundation for National Excellent Ph.D Thesis Author (Grant No. 20201162) and partially sponsored by National Natural Science Foundation of China (Grant No. 41304024). The authors would like to thank the editor in chief and the anonymous reviewers for their valuable comments and improvements to this manuscript.

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