Chapter 44
An Initial Evaluation About BDS Navigation Message Accuracy

Zhihang Hu, Guo Chen, Qiang Zhang , Jing Guo, Xing Su, Xiaotao Li, Qile Zhao and Jingnan Liu

Abstract In this paper, the accuracy of the trial operation stage BeiDou Navigation Satellite System (BDS) navigation message was analyzed and evaluated from January to December in 2012. The main content of the Beidou performance assessment was briefly introduced together with availability of Beidou precise ephemeris. Then, according to the Beidou mixed multi-satellite constellation characteristics, calculation formula of signal in space was derived, which is exactly suitable for Beidou system. Based on the Beidou precise ephemeris which derived from Position And Navigation Data Analysis software (PANDA) and BeiDou Experimental Tracking Stations (BETS), the accuracy of Beidou broadcast ephemeris, clock errors, Beidou system ionospheric correction model (BeiDou Klobuchar) and the pseudorange Single Point Positioning (SPP) were analyzed in details.

Keywords BeiDou/BDS/Compass · SISRE/URE · BeiDou Klobuchar · Single point positioning · PANDA

44.1 Introduction

Global Navigation Satellite System (GNSS) signal in space performance plays a key role in the accuracy of satellite navigation message and integrity monitoring [1]. GNSS Signal in Space Range Error (SISRE) is the fidelity between the actual value and the predictive value of the navigation message. It reflects the accuracy of predicted navigation ephemeris and clock error, and ultimately affects the

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positioning accuracy of real-time navigation users. BeiDou Navigation Satellite System (BDS), which is self-constructed, independently operated and compatible with other satellite navigation systems in the world, is steadily being built as the "three-step plan [2]", As a result, evaluating the signal in space performance of the rapid development of the BeiDou System is of great significance for people to understand the BeiDou System itself running status and its follow-up development.

On the basis of accumulating successful experience of Beidou I experiment satellite system (Beidou-1), China started the construction of the BeiDou phase II (BeiDou-2) in 2004. China successfully sent the first MEO satellite Compass M-1 into orbit in 2007, which indicates that the construction of China's satellite navigation system substantively entered the second step of the "three-step plan". In 2011, there has been 3 GEOs and 4 IGSOs successfully being placed into their slots, with initially regional navigation and positioning capacity. At the end of year 2011, China announced Beidou regional satellite system stepped into trial operation stage. Until December in 2012, 5 synchronous geostationary satellites (GEO), 5 inclined geosynchronous satellites (IGSO) and 4 medium earth orbit satellites (MEO) have been put into their slots, which achieved the goal of building "5GEO + 5IGSO + 4MEO" regional satellite system (See Fig. 44.1). And the

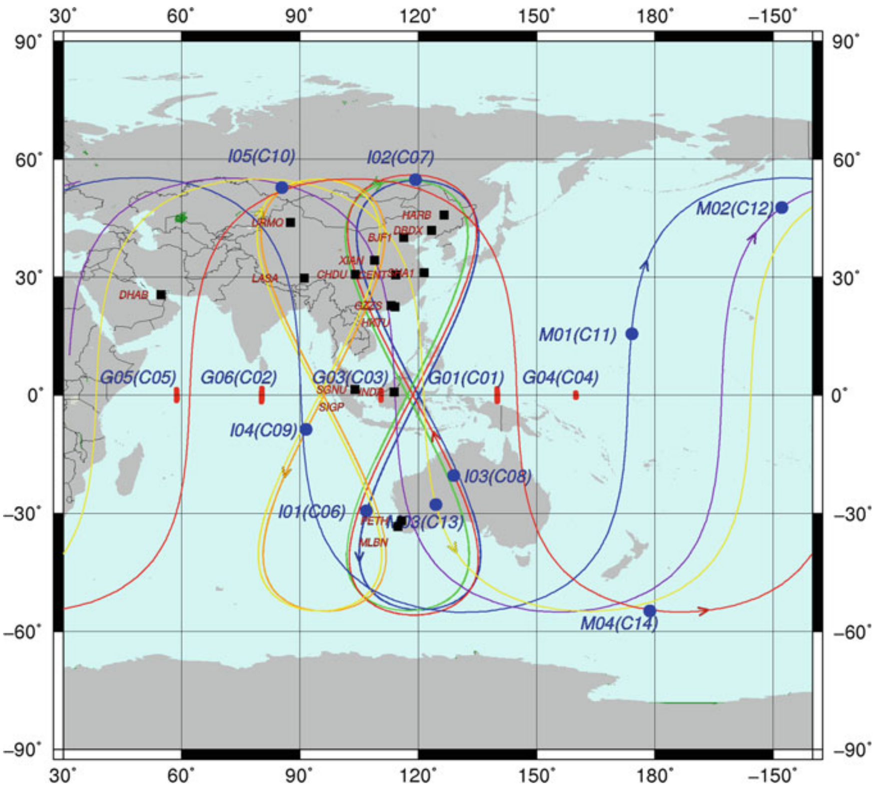

Fig. 44.1 5GEO + 5IGSO + 4MEO Beidou satellite footprint and BETS station distribution

Signal in Space Interface Control Document (ICD) of the Beidou system was announced in detail.

In this paper, the accuracy of the trial operation stage BDS navigation message was analyzed and evaluated from January to December in 2012. Firstly, the main content of the BDS performance assessment and availability of BDS precise ephemeris are briefly introduced respectively. Then, according to the characteristics of BDS mixed multi-satellite constellation, calculation formula of space signal accuracy is derived, which is exactly suitable for BDS. Last but not least, based on the BDS precise ephemeris and BDS Experimental Tracking Stations (BETS), which is established by Wuhan University, the accuracy of BDS predicted ephemeris, clock errors, BDS ionospheric correction model (BDS Klobuchar) and the pseudorange Single Point Positioning (SPP) are analyzed in details.

44.2 BDS Performance Evaluation Content and Precise Ephemeris

The satellite position error and clock error of the navigation message are the important component of SISRE and may influence the precision of navigation and positioning for real-time navigation user. Additionally, lacking of double frequency observation data, the precision of navigation and positioning calculated by single frequency will be under the influence of ionospheres' error. The main contents of this article will be analyzed as follow:

- BDS Broadcast ephemeris accuracy

For the pos-processing reason, the precise ephemeris is not available for real time positioning users. Master Control Station forecasts the orbit and clock error of the navigation satellites according to the field data provided by the ground monitoring station and transfers them to satellites in advance, then broadcasts to users. But this may lead to an error between satellites' real orbits and the prediction. The usually evaluation method is to compare navigation ephemeris with the post-processing precise one in the orbit coordinate system (namely, the radial, tangential and normal direction) accuracy.

- BDS Broadcast clock error accuracy

The clock error accuracy is the important component of the Space signal accuracy. The clock error precision will be calculated based on the precise clock offset.

- BDS Klobuchar ionospheric model accuracy

Ionospheric error mainly influence the single frequency users' positioning accuracy. The BDS provides modified Klobuchar eight parameters ionospheric model, the refresh rate is 2 h. Base on the GIM Ionospheres model published by

CODE center, the BDS Klobuchar ionospheric model accuracy evaluation will be conducted.

The assessment of the BDS broadcast ephemeris needs the higher accuracy satellite position and clock error as reference. As BDS now is trial operation phase, there are no available precise orbit and precise clock error released by BDS official. With the help of the observation data from "BeiDou observation and experiment network (BETS)" built by Wuhan University for scientific research purpose, the BDS satellites precise orbit and clock error are derived using PANDA software, which is self-developed by Wuhan University. BETS consist of 20 ground tracking stations, 11 stations are uniform distribution in China, and another stations distribute in Asia–pacific countries such as Australia, Singapore, and Indonesia and so on. The BETS ground tracking stations distribute in Asia–pacific area properly and quite a number of data can be achieved, which is useful for BDS precise orbit determination (POD). The radial precision of 10 cm [3] is achieved from BeiDou POD, which satisfies the evaluation of BeiDou SISRE.

44.3 Methods of BDS Performance Evaluation

- Beidou SISRE derivation

Signal in space accuracy is the fidelity of the navigation information (navigation ephemeris and clock errors) accuracy. There are a lot of literatures about the performance and features of GPS and GLONASS space signals [4–6], having deduced the corresponding formula of the space signal accuracy. For example, the formula of GPS SISRE is:

$$SISRE = \sqrt{(R-T)^2 + \frac{1}{49}(A^2 + C^2)} \tag{44.1}$$

where, A, C, R, T are respectively the ephemeris position errors and satellite clock in the satellite orbit coordinate system.

At present, BeiDou Satellite System constellations are mainly composed of GEOs and IGSOs composition with high orbital altitude, and is obvious different from GPS and other satellite navigation systems. The formula (44.1) is not suitable to calculate current BeiDou Satellite System SISRE.

Assuming that the Earth as an ideal sphere, orbital coordinate system is established (see Fig. 44.2), with the Earth's mass of center as an origin, connecting geocentric and satellite ***S*** mass of center and pointing to satellite setting up ***r*** axis (radial), the satellite ***S***'s flight direction (tangential) as ***a*** axis, and according to the right-hand rule established ***c*** axis (normal). Assuming the distance of the satellite to the geocentric and the radius of the earth are D_s and D_e, arbitrary ***P*** with the zenith distance and azimuth $\theta,$ is satisfied with the joint density probability $\rho(\theta) \propto \sin\theta$ in the satellite signal coverage $(0 \le \theta \le 2\pi,\ \ 0 \le \theta \le \theta_{\max} = \cos^{-1}(D_e/D_s))$. According to the literature [4], the general formula of the GNSS average SISRE is:

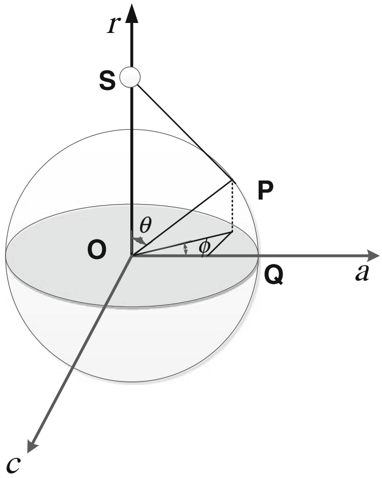

Fig. 44.2 The orbit coordinate system position error projection

$$SISRE = \sqrt{(\alpha R - T)^2 + \beta(A^2 + C^2)} \tag{44.2}$$

$$\alpha = \frac{1}{D}\int_0^{\theta_{\max}}\int_0^{2\pi} \frac{D_s - D_e\cos\theta}{\sqrt{D_e^2 + D_s^2 - 2D_eD_s\cos\theta}}\sin\theta d\phi d\theta$$

$$\beta = \frac{1}{D}\int_0^{\theta_{\max}}\int_0^{2\pi} \frac{D_e^2\sin^2\theta\cos^2\phi}{\sqrt{D_e^2 + D_s^2 - 2D_eD_s\cos\theta}}\sin\theta d\phi d\theta$$

where, $D = 2\pi(1 - \cos(\theta_{\max}))$ is the coverage area of the satellite footprint.

Supposing that the Earth's radius is 6,371 km, the height of MEO orbit is 21,500 km, the GEO orbit height of 21,500 km, using the above formula we can get the formula for the BeiDou system SISRE:

$$\begin{aligned} SISRE_{BDS(GEO,IGSO)} &= \sqrt{(0.99R - T)^2 + \frac{1}{128}(A^2 + C^2)} \\ SISRE_{BDS(MEO)} &= \sqrt{(0.98R - T)^2 + \frac{1}{54}(A^2 + C^2)} \end{aligned} \tag{44.3}$$

If satellite clock error is removed, then, we obtain:

$$\begin{aligned} SISRE^{Orbit\ only}_{BDS(GEO,IGSO)} &= \sqrt{(0.99R)^2 + \frac{1}{128}(A^2 + C^2)} \\ SISRE^{Orbit\ only}_{BDS(MEO)} &= \sqrt{(0.98R)^2 + \frac{1}{54}(A^2 + C^2)} \end{aligned} \tag{44.4}$$

The formula (44.3–44.4) will be used to evaluate the Beidou SISRE performance.

In addition, to evaluate the Beidou SISRE also need considering the following issues:

- Satellite antenna phase center offset

The satellite position calculated by the BeiDou navigation ephemeris is relative to the position of the satellite antenna phase center offset (PCO), while BeiDou precise orbit is relative to the mass center of satellite. Thus the transformation is needed from the mass of center to the satellite antenna phase center.

- The unification of the time system and the coordinate system

The BeiDou broadcast ephemeris time is BeiDou Time (BDT). Duo to using different reference clock for orbit determination, there exists an offset between the precision clock error and broadcast clock error. It can be removed by standard deviation (STDEV) statistical method. The BeiDou broadcast ephemeris is based on China Geodetic Coordinate System 2000 (CGCS2000) coordinate system and the precise orbit data is based on ITRF2008 coordinate system. Both of them exist differences. However, this difference is only a few centimeters of the order of magnitude [7, 8], so this difference will be neglected in this paper analysis.

- The calculation of the BeiDou system GEO satellite position

The GEO satellite orbital inclination and eccentricity are very close to zero, so following GPS broadcast ephemeris parameters form to fit the BeiDou GEO satellite orbit may diverge due to the matrix singularity. The BeiDou GEO satellite ephemeris parameters use the so-called coordinate rotation method to reduce the parameter fitting error. When the BeiDou users use the BeiDou GEO navigation ephemeris, it also required the corresponding coordinate rotation in order to calculate the correct position of the satellite. The detailed algorithm please refers to BeiDou ICD [9].

44.4 Results and Discussion of BeiDou Performance Evaluation

The BDS SISRE accuracy and positioning accuracy were assessed for the whole year of 2012. Observation data was collected from the BETS, while BDS precise orbit and clock products were obtained with PANDA in post-processing mode.

1. Analysis of BDS SISRE

SISRE depends mainly on the broadcast ephemeris error and clock error. In normal scenarios, ephemeris of GEO and IGSO of BDS navigation message updates every 60 min, including the forecast clock error. Frequently updating ephemeris is helpful to improve broadcast satellite orbit and clock precision. Shown in Fig. 44.3 was the standard deviation of differences between broadcast and precise clock products, and standard deviation of most broadcast clock error falls in the range of 2 - 8 ns during the day 001 to 336 of year 2012.

Standard deviation of clock error for C01 was large (about 12 ns) during the first 3 months, and the precision increased to 4 - 8 ns from April on. For C03, the standard deviation fluctuated from 2 - 4 ns to 12 ns (in the middle period), and the precision was then improved (2 - 4 ns) near the end year of 2012. The precision of clock error for IGSOs (C06 - C10) is generally better compared to GEOs (C0 - C05), most of which are stably within 2 - 6 ns (STDEV). However, the precision of forecast clock errors for MEO C11 - C12 increased sharply after their working well for 3 months.

According to Eq. (44.3), statistics of SISRE for each satellite of BDS is shown in Fig. 44.4. Since IGSO could be tracked for a long time in China area and broadcast ephemeris updates every hour, the precision of SISRE is 1.2 m (RMS) on average and keeps relatively stable. Different from IGSOs, GEOs stay "static" at equatorial plane and geometry changed slowly, leading to worse clock precision than IGSOs. The SISRE of MEOs built in June of 2012 was gradually improved from 3.5 to 1.2 m. Generally speaking, SISREs of all three types (GEOs, IGSOs and MEOs) were increasing continuously, with the improvement in number and distribution of BDS tracking stations, as well as that in system performance of BDS. Up to December in 2012, the average precision of 5GEO/5IGSO/4MEO is about 1.5 m (RMS).

Shown in Fig. 44.5 is the statistical result of SISRE, only with orbit forecasting error taken into account. Among the three types of constellation, MEOs had the best precision, and GEOs the worst. Compared with Fig. 44.4, SISRE with forecasting clock error not taken into account was obviously better than the opposite, which indicated that clock error accounted the main part of the SISRE.

2. BeiDou Klobuchar ionosphere model accuracy

To improve the navigation and positioning precision for the regional single frequency users, BDS has built the BeiDou Klobuchar model for ionospheric

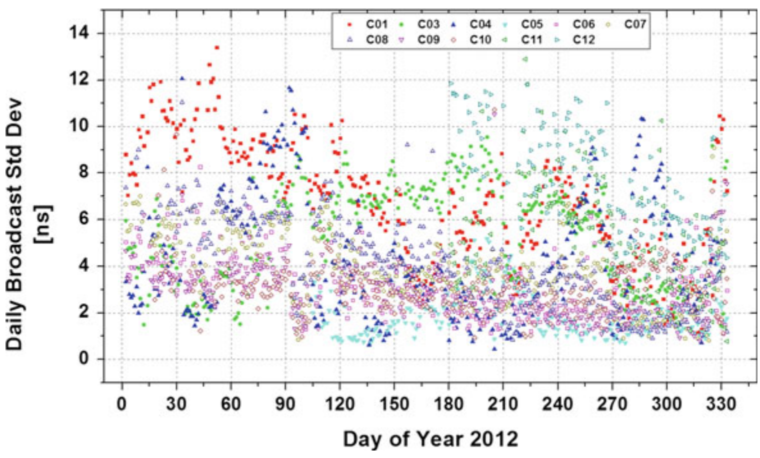

Fig. 44.3 Daily broadcast clock residual w.r.t WHU precise clock

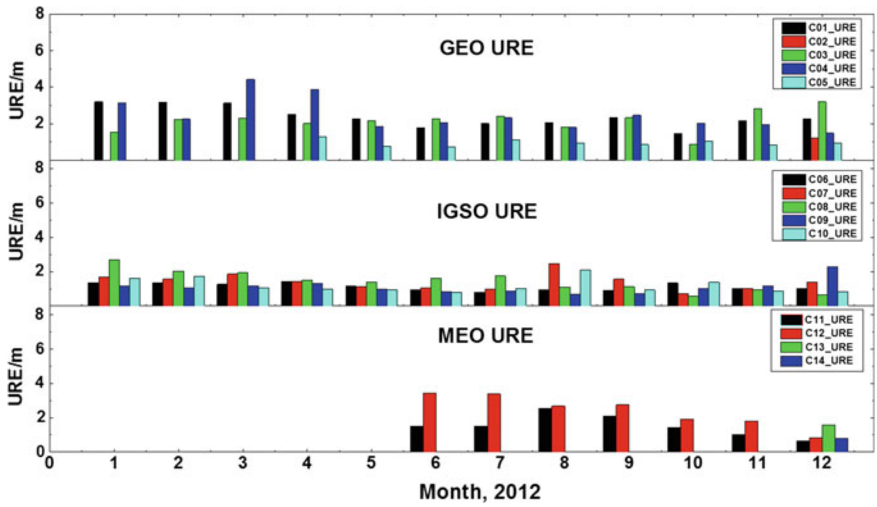

Fig. 44.4 Statistics of BeiDou SISRE accuracy

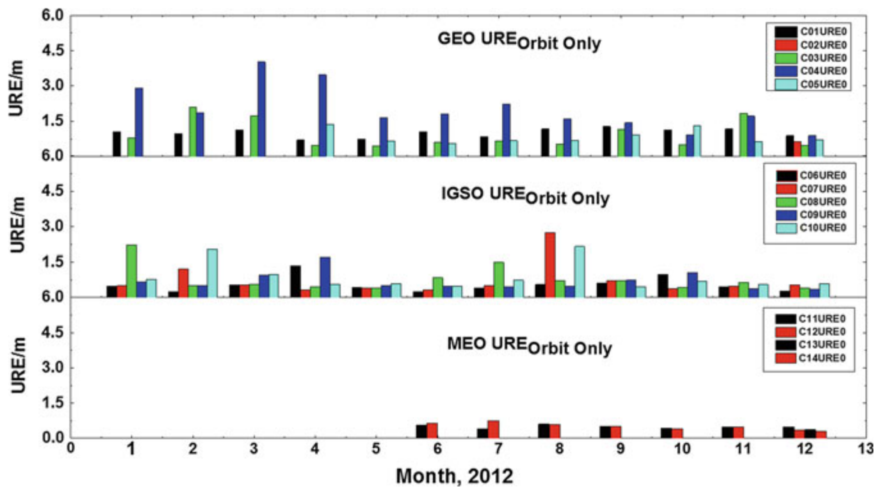

Fig. 44.5 Statistical result of SISRE only with forecasting clock error taken into account

correction. The model is obtained by solving the real dual-frequency GNSS observations from a regional tracking network in China. Due to the lack of data in the southern hemisphere, the ionospheric corrections in the southern hemisphere are calculated by means of symmetry with the northern hemisphere.

The Global Ionosphere Maps (GIM) provided by CODE is used as the reference ionospheric correction values in this paper. And then the vertical ionospheric correction residuals of BeiDou Klobuchar model are calculated for December 2012, which is shown in Fig. 44.6. It is can be seen from Fig. 44.6 that the

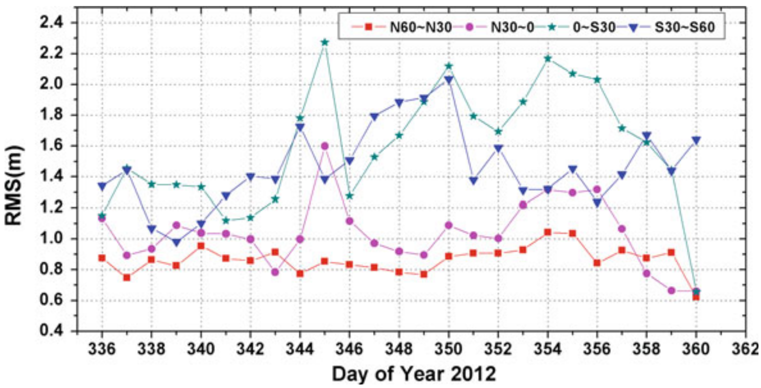

Fig. 44.6 The precision of BeiDou Klobuchar model in different latitude zone. The *horizontal axis* is the Day of Year in 2012 (unit: day) and the *vertical axis* is the RMS of BeiDou Klobuchar ionospheric delay correction residuals (unit: m). The *red symbol* is mean RMS from N60° to N30°, respectively, the *pink symbol* is the mean RMS from N30° to 0°, the *green symbol* is the mean RMS from 0° to S30°, and the *blue symbol* is the mean RMS from S30° to S60°

correction precision of BeiDou Klobuchar model is about 1.0 m in the northern hemisphere, while in the southern hemisphere the precision decreases to 1.5 m. This is mainly because that in BeiDou Klobuchar model the southern hemisphere adopts the same parameters with the northern hemisphere by means of symmetry.

For further analysis, the correction ratio of BeiDou Klobuchar model is calculated for 5 chosen stations from BETS tracking network. The correction ratio equation used in the paper is:

$$Ratio = \frac{1}{n}\sum_{i=1}^{n}\left(1 - \frac{|Klobuchar_{BDS} - GIM_{GPS}|}{GIM_{GPS}}\right) \times 100\,\% \tag{44.5}$$

As shown in Fig. 44.7, the correction ratio of BeiDou Klobuchar model in China is almost above 70 %. This is convinced by using the real dual-frequency BeiDou observations as the reference value, and [10] shares the same conclusion. By comparing the ratios of stations in the perspective of latitude, it can be seen that the correction precision is higher in the mid-latitude area than in the low latitude area.

3. Analysis of BDS pseudorange positioning accuracy

In 2012, 6 BeiDou satellites were launched, including 2 GEOs and 4 MEOs, lending to a significant change in the constellation structure and a dramatic improvement in DOP value. Table 44.1 listed the change of constellation, so as to analyze the impact of constellation on positioning accuracy. The service area covers 55°E ~ 160°E, 55°S ~ 55°N. Three typical observing stations were selected to analyze the positioning accuracy of BDS in 2012, and the information of these stations was shown in Table 44.2.

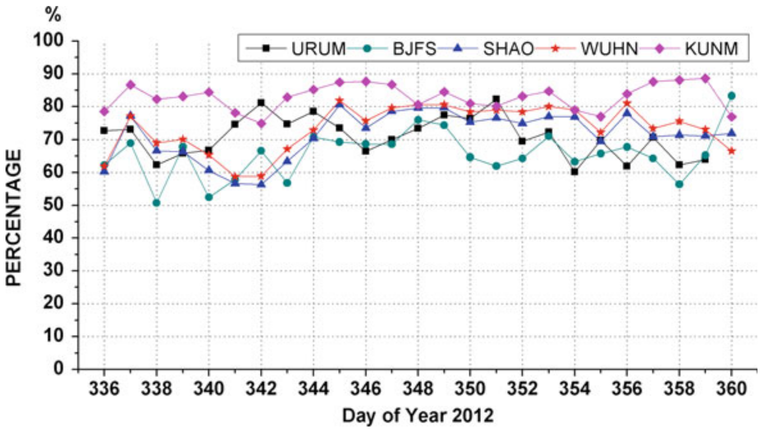

Fig. 44.7 BeiDou Klobuchar model ionospheric delay correction precision. The *horizontal axis* is the Day of Year in 2012 (unit: day) and the *vertical axis* is the correction percentage of BeiDou Klobuchar ionospheric model. The *black symbol* is the correction of URUM station, respectively, the *green* represents BJFS, the *blue* represents SHAO, the *red* represents WUHN, and the *pink* represents KUNM

Table 44.1 Beidou construction stages

Number	Constellation	Duration
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–now

Table 44.2 Typical BeiDou tracking station information

Site	ID	Obs. type	Latitude	Longitude	Receiver privider
Beijing	BJF1	B1I/B2I	+40.0	+116.3	UNICORE
Wuhan	CENT		+30.5	+114.4	UNICORE
Perth (Australia)	PETH		−31.9	+115.8	UNICORE

The positioning algorithm for BDS pseudo range was a little different from GPS: (1) Coordinates transformation was required when computing GEO satellite position with broadcast ephemeris; (2) Beidou Klobuchar ionosphere model could be use to correct ionospheric delay in single-frequency positioning, which is computed in a different way from GPS [10].

Figures 44.8, 44.9 and 44.10 show the pseudo range stand-alone result of single frequency (B1I). When the constellation was 3GEO + 4IGSO, positioning precision was about 10 m in horizontal and 15 m in vertical (95 %). When another GEO (C05) was added and the structure became 4GEO + 5IGSO, geometric

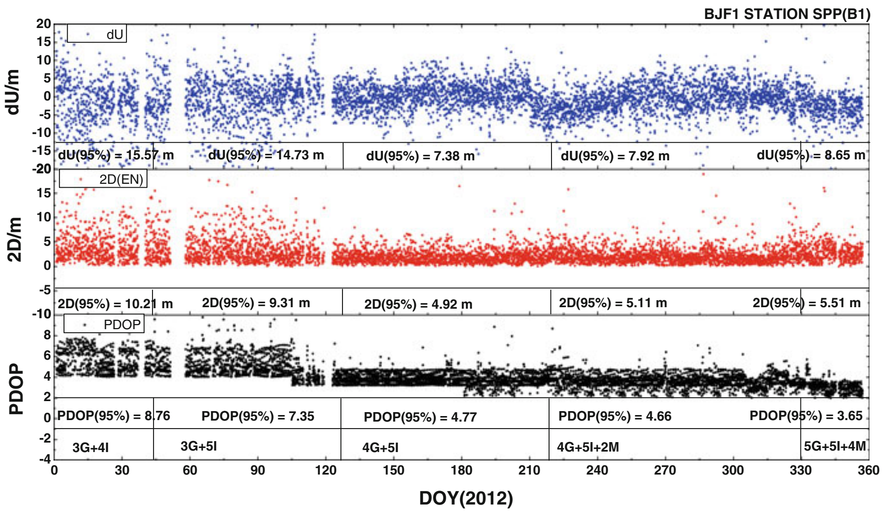

Fig. 44.8 Beijing station SPP precision (January–December, 2012)

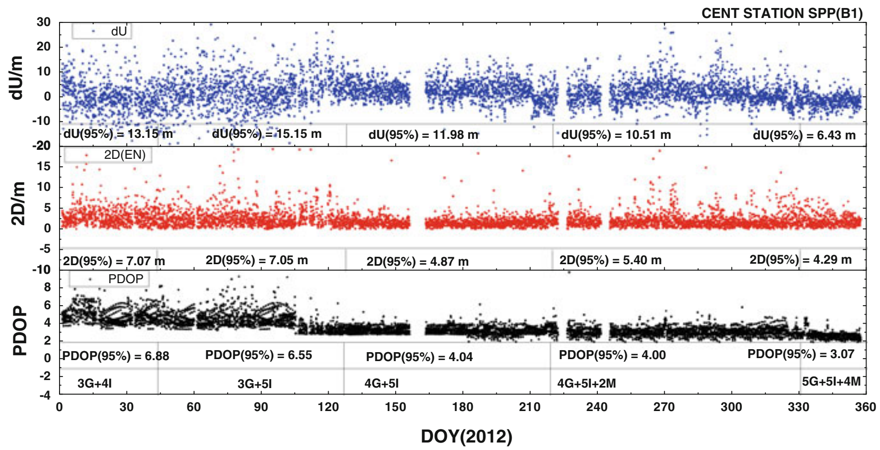

Fig. 44.9 Wuhan station SPP precision (January–December, 2012)

condition at observing station was improved dramatically, and the PDOP value was reduced by half. Correspondingly, the positioning precision improved. In 4GEO + 5IGSO + 2MEO constellation, the contributions of additional two MEOs to geometric conditions and positioning precision were not that obvious, since tracking time is relatively short and interval of ephemeris uploading is longer than GEOs and IGSOs. Precision of pseudo range positioning at the condition of 5GEO + 5IGSO + 4MEO is improved, with horizontal precision better than 6 m (95 %) and vertical precision better than 10 m (95 %). The results show that the

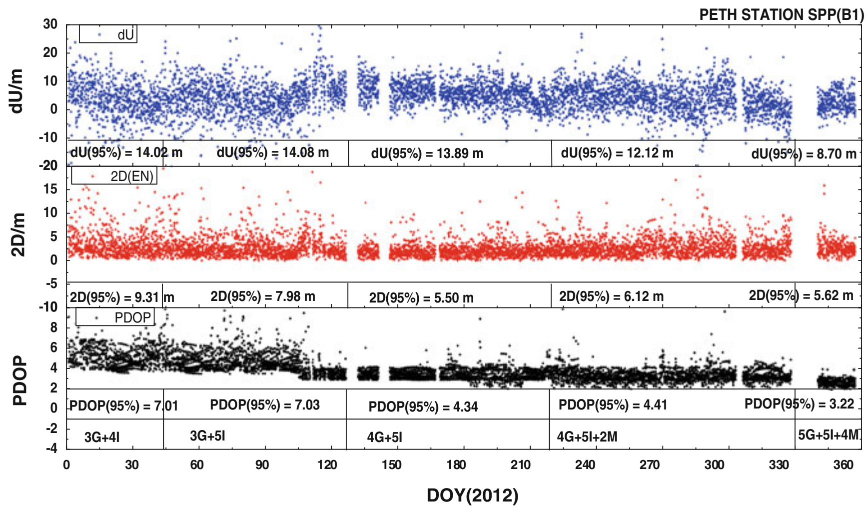

Fig. 44.10 Perth station SPP precision (January–December, 2012)

precision of BeiDou pseudo range positioning for choosen stations has meets the service specification of horizontal 10 m and vertical 10 m.

44.5 Conclusion

Based on the large BeiDou observation data from January to December in 2012, the BeiDou broadcast ephemeris and clock precision is assessed with BeiDou precise ephemeris and clock computed by PANDA software. The BeiDou Klobuchar ionosphere model is also compared with higher precise GIM released by CODE and the navigation positioning accuracy is investigated as well choosing typical tracking stations in the BeiDou service volume. From the statistics result, we can draw conclusions as follows:

- Compared with precise clock data, the broadcast clock error precision ranges from 4 to 6 ns (STDEV)
- Signal in Space error accuracy better than 1.5 m
- BeiDou ionosphere Klobuchar model correction ratio is approximately 70 %. And northern sphere is generally better than southern sphere duo to lack of southern ionosphere monitor observation data.
- With rapid constellation development of the BDS the signal in space performance of BDS becomes better and better. The positioning accuracies of initial stage (3GEO + 4IGSO) are 10 m (Horizontal) and 15 m (Vertical). And these accuracies are further improved up to 6 and 10 m respectively. The typical SPP

statistical results show that the single frequency receiver positioning accuracy generally meets the Asian–pacific region service specification of horizontal 10 m and vertical 10 m.

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