Analysis and Modeling of the Inter-system Bias Between BDS-2 and BDS-3

Ziyuan Song[1,2], Junping Chen[1(✉)], Bin Wang[1], and Chao Yu[1,2]

[1] Shanghai Astronomical Observatory, Chinese Academy of Science, Shanghai 200030, China
{songziyuan, junping}@shao.ac.cn
[2] University of Chinese Academy of Science, Beijing 100049, China

Abstract. The BDS-3 system has provided positioning navigation and timing (PNT) service since December 2018, while applications show that there is inter-system bias (ISB) between the BDS-2 and BDS-3 systems. Origin of the ISB and its influences on Beidou positioning are analyzed, and then the positioning algorithm including ISB is presented in order to improve Beidou navigation and positioning precision from the perspective of users. Judging by improvement effect on the BDS-2 and BDS-3 joint positioning, three ISB estimation models, such as white noise model, piecewise constant model, and random walk model, are analyzed, using Asia-Pacific observations and precision orbit and clock products of IGS. Results show that ISB estimation methods can effectively improve the precision of BDS-2 and BDS-3 joint standard point positioning (SPP), and the improvement of three methods can reach 22%, 23% and 36% respectively, while for BDS-2 and BDS-3 joint precise point positioning (PPP), the improvement is 17%, 16% and 18% respectively.

Keywords: BDS-2 · BDS-3 · Inter-system bias · Standard point positioning · Precise point positioning

1 Introduction

The third generation of BeiDou satellite navigation system (BDS-3) has provided PNT services since December 27, 2018, marking that BDS has become the third system that can provide global positioning and navigation services after GPS, and GLONASS. On the basis of BDS-2, BDS-3 providing services that will greatly increase the number of Beidou visible satellite in the Asia-Pacific region. This can not only improve the navigation and positioning accuracy, but also ensure the integrity of PNT services. Yang et al. analyse the BDS-3's PNT service performance and figured out that BDS-3 satisfied the requirements of design in orbit determination accuracy, satellite clock accuracy, signal-in-space accuracy and PNT service performance [1].

However, when performing BDS-2 and BDS-3 joint positioning, the significant increase in the number of visible satellites hasn't brought obviously precision improvement. The reason is that there is ISB between BDS-2 and BDS-3, which inhibits the improvement of positioning precision. Therefore, when jointly using BDS-2 and BDS-3 satellites for positioning, the influences of ISB have to be considered.

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Many scholars have conducted in-depth research on the problem of ISB estimation in the multi-GNSS fusion positioning. Zhang et al. analyse the effect of ISB estimation on the GPS and GLONASS joint positioning [2]. Liu et al. study the ISB estimation method of GPS/BDS joint PPP, and proposes the optimal estimation method of ISB suitable for GFZ, CODE and WHU precise products [3]. Wang et al. uses MGEX observations to analyse the influence of ISB in GPS/GLONASS/Galileo/BDS multi-GNSS PPP, and results show that ISB of different GNSS within one day are very stable [4]. Zhou et al. analyse the stochastic model of ISB estimation in multi-GNSS PPP, and the precision of ISB estimated using three model, white noise model, random walk model, and piecewise constant model, are compared, and the optimal estimation methods for different precise products are also proposed [5]. Jiao et al. analyse the effect of ISB on BDS-2 and BDS-3 joint PPP [6]. Zhang et al. further analyse the time group delay(TGD) deviation between BDS-2 and BDS-3 and also the precision improvement of the BDS-2 and BDS-3 joint positioning after correcting the TGD deviation [7].

Focusing on the ISB between BDS-2 and BDS-3, this paper analyse the origins of the ISB and present the ISB estimation model, and the role of ISB estimation model in improving the precision of BDS-2 and BDS-3 joint positioning is also evaluated.

2 ISB in BDS-2 and BDS-3 Joint Positioning

2.1 The Origins of ISB in BDS-2 and BDS-3

BDS-2 and BDS-3 are maintained by their respective operation control systems. Ensemble of time-keeping clocks for each system is independent of each other, and the time traceability accuracy is within the range of 1 ns. These two systems have different types of receivers in the ground monitoring network. Although receivers of BDS-3 can also track BDS-2 satellites, the stability of the hardware delay needs to be improved. Therefore, although the consistency between BDS-2 and BDS-3 is maintained to the maximum extent during construction, due to various factors, there may be systematic biases between BDS-2 and BDS-3, which may affect navigation and positioning accuracy.

2.2 Effect of ISB on BDS-2 and BDS-3 Joint Positioning

After BDS-3 officially providing services, the number of BDS satellites has increased from 16 to 37 (as of 2019.11.23). Figures 1 and 2 respectively show the number of global visible satellites of BDS before and after the on-line of BDS-3 system. The number of visible satellites increased from 8-10 to more than 14 for the Asia-Pacific region, which, in theory, will inevitably lead to better positioning precision.

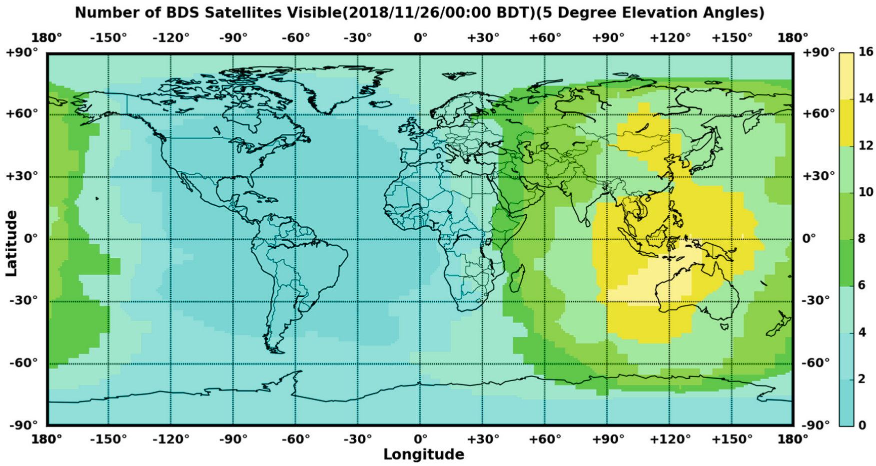

Fig. 1. The number of visible satellite in the world area (2018.11.26) [8]

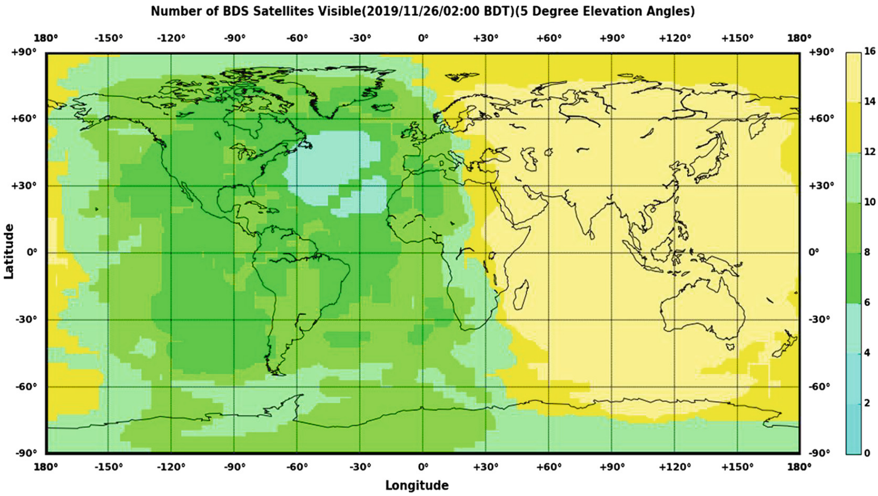

Fig. 2. The number of BDS visible satellite in the world area (2019.11.26) [8]

However, when performing BDS-2 and BDS-3 joint SPP, the positioning results did not reach the expected precision due to the ISB between BDS-2 and BDS-3. The RMS error of the coordinates for the IGS KAT1 station can be seen from Fig. 3. Compared to BDS-2 SPP alone, inclusion of BDS-3 satellites don't provide better positioning precision. Instead, the fluctuations of positioning results are more significant.

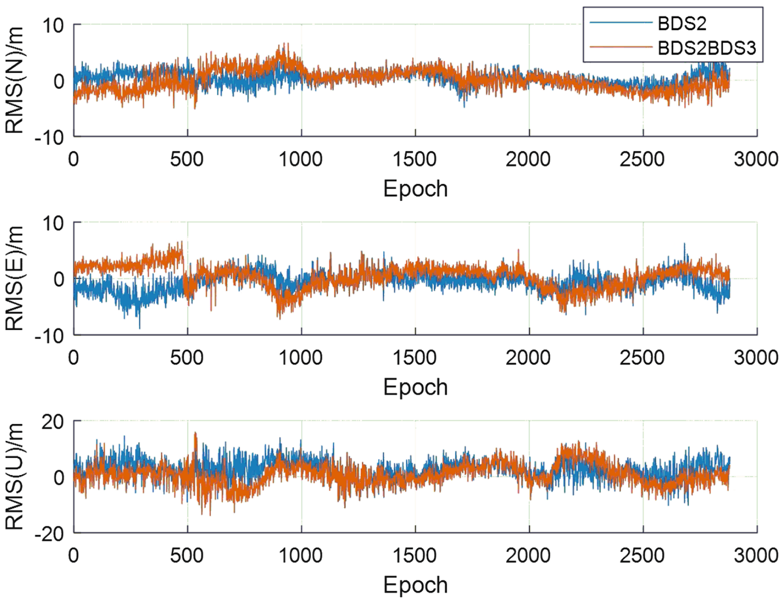

Fig. 3. SPP resolution result of BDS-2 and BDS-2, 3 joint

Table 1 shows the positioning results of BDS-2 SPP alone and also BDS-2 and BDS-2 joint SPP, based on the three-day (day of year 212–214) observations of two IGS stations, KAT1 (Australia) and IISC (India). From the table, we can see that compared with BDS-2 SPP alone, BDS-2 and BDS-3 joint positioning does not bring an obvious improvement of positioning precision. And the precision of BDS-2 and BDS-3 joint positioning even become worse, therefore, the ISB between BDS-2 and BDS-3 must be taken into consideration for joint positioning.

Table 1. RMS of SPP resolutions of BDS-2 and BDS-2, 3 joint positioning

DOY	STA	KAT1 RMS (m)				Improvement	IISC RMS (m)				Improvement
		N	E	U	3D		N	E	U	3D	
212	BDS-2	0.847	1.488	2.527	3.052	−29%	1.003	1.623	3.555	4.035	3%
	BDS-2, 3	1.519	1.894	3.091	3.93		0.824	1.745	3.392	3.902	
213	BDS-2	2.552	0.941	6.487	7.034	13%	0.932	1.732	3.744	4.229	20%
	BDS-2, 3	2.876	2.062	4.974	6.104		1.363	1.812	2.515	3.386	
214	BDS-2	1.71	1.208	3.071	3.716	Accessed 34%	1.003	1.263	3.555	4.035	−5%
	BDS-2, 3	1.461	1.659	4.443	4.963		1.187	1.464	3.784	4.227	

3 BDS-2 and BDS-3 Joint Positioning Model and ISB Estimation Model

3.1 BDS-2 and BDS-3 Joint Positioning Model

3.1.1 Standard Point Positioning Model

The BDS-2 and BDS-3 Joint SPP Model can be defined as:

$$\begin{cases} P_{BDS-2} = \rho + c \cdot \delta_{rcv-2} - c \cdot \delta^{sat} + \delta_{trop} + \delta_{others} \\ P_{BDS-3} = \rho + c \cdot \delta_{rcv-3} - c \cdot \delta^{sat} + \delta_{trop} + c \cdot \delta_{ISB} + \delta_{others} \end{cases} \tag{1}$$

where, P_{BDS-2}, P_{BDS-3} respectively represents pseudoranges of BDS-2 and BDS-3; and δ_{rcv-2}, δ_{rcv-3} respectively corresponding to the receiver clock of BDS-2 and BDS-3. δ^{sat} is the satellite clock, δ_{trop} is the tropospheric delay, δ_{ISB} represents the inter-system bias between BDS-2 and BDS-3, δ_{others} includes other residual errors. Iono-free combination P_{IF} is used to eliminate the first-order of ionospheric delay:

$$P_{IF} = \frac{1}{f_1^2 - f_2^2}\left(f_1^2 P_1 - f_2^2 P_2\right) \tag{2}$$

Where, f_1 and f_2 represents the corresponding signal frequencies.

3.1.2 Precise Point Positioning Model

The BDS-2 and BDS-3 Joint PPP Model can be defined as:

$$\begin{cases} P_{BDS-2} = \rho + c \cdot \delta_{rcv-2} - c \cdot \delta^{sat} + \delta_{trop} + \delta_{others} \\ \phi_{BDS-2} = \rho + c \cdot \delta_{rcv-2} - c \cdot \delta^{sat} + \lambda N_{BDS-2} + \delta_{trop} + \delta_{others} \\ P_{BDS-3} = \rho + c \cdot \delta_{rcv-3} - c \cdot \delta^{sat} + \delta_{trop} + c \cdot \delta_{ISB} + \delta_{others} \\ \phi_{BDS-3} = \rho + c \cdot \delta_{rcv-3} - c \cdot \delta^{sat} + \lambda N_{BDS-3} + \delta_{trop} + c \cdot \delta_{ISB} + \delta_{others} \end{cases} \tag{3}$$

Where, ϕ_{BDS-2}, ϕ_{BDS-3} is the carrier phase observations of BDS-2 and BDS-3, N_{BDS-2}, N_{BDS-3} is the phase ambiguity of BDS-2 and BDS-3, δ_{ISB} represents the inter-system bias between BDS-2 and BDS-3.

3.2 BDS-2 and BDS-3 ISB Estimation Model

3.2.1 White Noise Model (WN)

Assuming that ISB between BDS-2 and BDS-3 follows Gaussian white noise distribution, and ISB of each epoch are independent of each one:

$$ISB(i) = N\left(0, \sigma^2\right) \tag{4}$$

White noise estimation is the simplest method with independent parameter between adjacent epochs. For SPP, since the range error of the pseudo-range is more than 0.3 m and some other errors are not considered, the ISB parameter may absorbed some other errors while estimating the ISB parameter in each epoch. Even though, the influence of ISB between BDS-2 and BDS-3 still can be corrected in this parameter. For PPP, since the errors are strictly corrected and the phase observation are used, we considered the ISB parameter is not polluted by other errors.

3.2.2 Piecewise Constant Model (PC)

Assuming the short-term stability of the ISB [3], and it can be fixed as a constant within a certain period of time:

$$ISB(i+1) = ISB(i) \tag{5}$$

Compared with WN model, this model reduces the number of estimation parameters and increases the number of redundant observations. The ISB parameters can also be estimated even with a small number of satellites.

3.2.3 Random Walk Model (RW)

Assuming that ISB has a random walk feature, the random walk model can be used to estimate it:

$$ISB(i+1) = ISB(i) + \omega_{ISB}, \omega_{ISB} \sim N\left(0, \sigma^2_{\omega_{ISB}}\right) \tag{6}$$

The random walk model uses the estimated ISB of the previous epoch, and its variance increases linearly with time, which can better describe the variation characteristics of ISB over time.

4 Precision Analysis of BDS-2 and BDS-3 Joint Positioning with ISB Estimation Model

4.1 Precision Analysis of BDS-2 and BDS-3 Joint SPP

Three ISB estimation methods of white noise model, piecewise constant model, and random walk model are used to perform BDS-2 and BDS-3 joint SPP using seven-day observations of the IGS, and the sampling time is 30 s. The pseudorange observations are processed using the Hatch phase smoothing method [9]. Tropospheric delay is calculated using the Saastamoinen model, meteorological parameters are obtained through GPT2w, and the projection function is VMF1. BDS B1B3I dual-frequency iono-free combination are used to eliminate the first-order of ionospheric effects [10]. The satellite position is calculated using the BDS broadcast ephemeris. Considering that the pseudorange noise is relatively large, other errors such as tide correction and satellite phase center correction can be ignored.

Figure 4 shows the positioning error in the three directions of NEU by four types of ISB estimation strategy. For the piecewise constant model, we set the length of effective time window to 20 min. It can be clearly seen from the figure that compared with the estimation strategy that does not estimate ISB, ISB estimating can effectively improve the precision of SPP positioning solution.

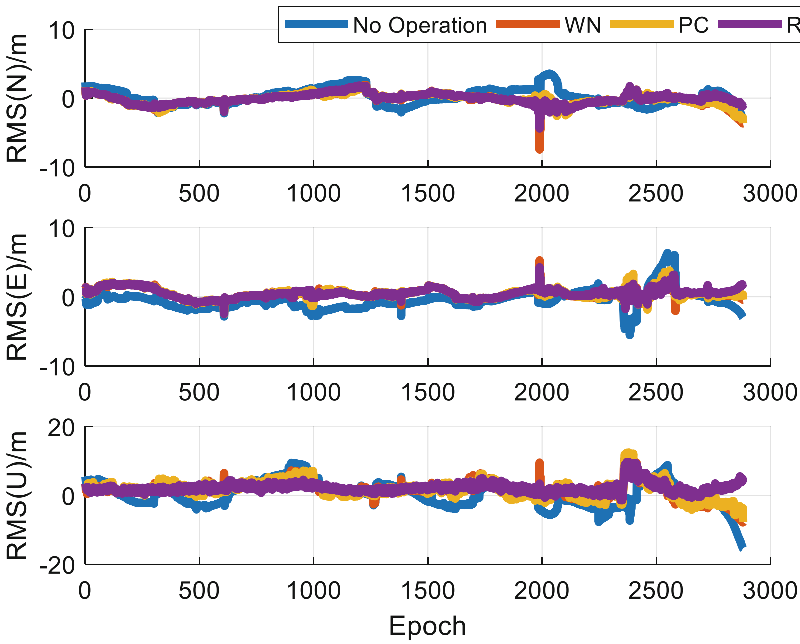

Fig. 4. SPP results with four different ISB estimation methods

Figure 5 shows the estimated ISB using three methods. It can be seen that ISB calculated by the white noise model and the piecewise constant model is subject to the influence of pseudorange noise, and the random walk model is constrained by adjacent epochs, and the estimated value is relatively stable.

Table 2 summarizes the average RMS error of BDS-2 and BDS-3 joint SPP during seven days using four types of ISB estimation strategies, without ISB estimation, and ISB estimation of white noise, piecewise constant and random walk model. From the table, we can see that, compared with the non-estimated ISB processing strategy, considering the influences of ISB, the 3D positioning precision of joint SPP can be improved by more than 20%. White noise model, piecewise constant model, and random walk model can improve the positioning precision by 22%, 23%, and 36%, among which the random walk model has the best positioning precision.

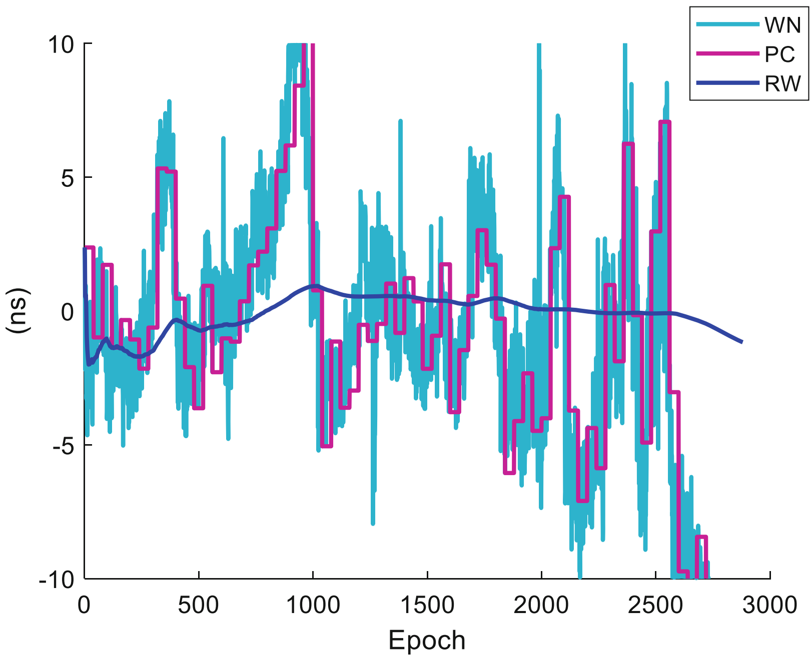

Fig. 5. ISB resolution with four different ISB estimation methods in SPP

Table 2. Comparison of the precision of four ISB estimation methods with SPP

	N	E	U	3D	Improvement percentage
No operation	1.187	1.464	3.784	4.227	–
White noise	0.832	0.815	3.078	3.291	22%
Piecewise constant	0.784	0.878	3.013	3.234	23%
Random walk	0.696	0.828	2.498	2.723	36%

4.2 Precision Analysis of BDS-2 and BDS-3 Joint PPP

Similar to SPP, three ISB estimation methods of white noise model, piecewise constant model, and random walk model are also used in performing BDS-2 and BDS-3 joint PPP. Precise orbit and clock products of Wuhan University (WHU) [11] are used to perform PPP processing on the seven-day observation data of the IGS station.

Figure 6 shows the PPP results obtained by using four processing strategy (ISB non-estimation, and ISB estimation using white noise model, piecewise constant model and random walk model). It can be seen that for joint PPP, the convergence precision of the four strategies is almost the same. Figure 7 shows ISB between BDS-2 and BDS-3 estimated by different estimation methods. It can be seen that ISB calculated by each method are also consistent.

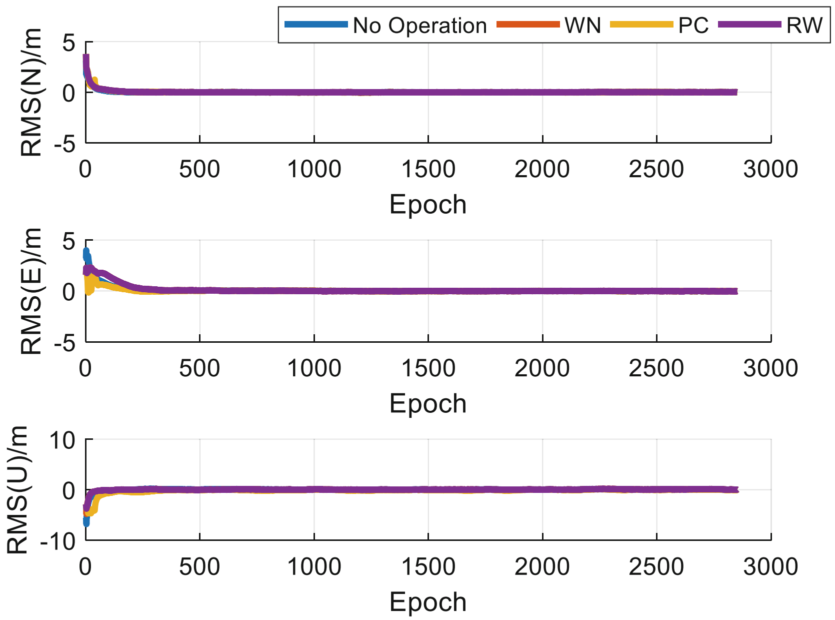

Fig. 6. PPP results with four different ISB estimation methods

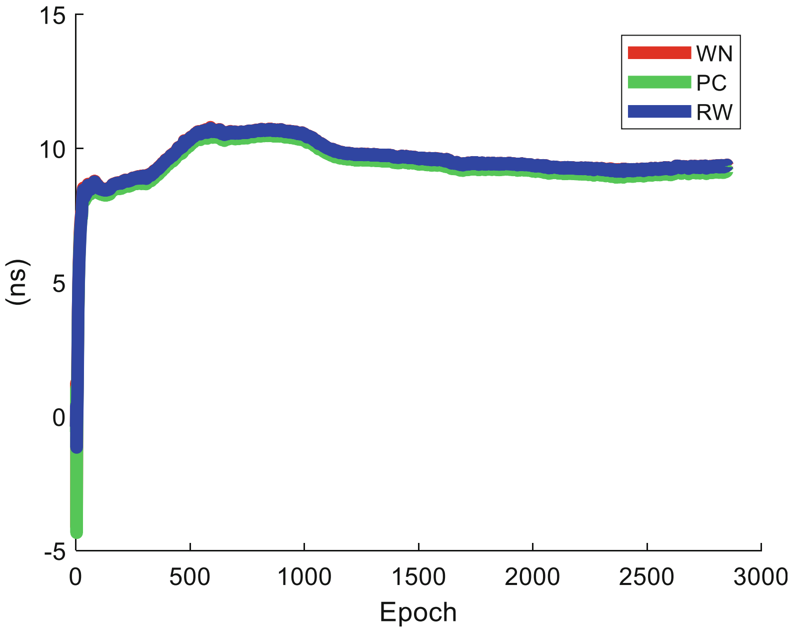

Fig. 7. ISB resolution with four different ISB estimation methods in SPP

Table 3 summarizes the average RMS error and time of 3D positioning for joint PPP using four types of ISB estimation strategies, without ISB estimation, and ISB estimation of white noise, piecewise constant and random walk model. The convergence criterion is defined when the component of positioning errors is less than 0.3 m and keeping within 0.3 m in the subsequent epochs. If the error exceeds the threshold, the convergence time is re-recorded. It can be seen that compared with ISB non-estimated processing strategy, when considering the influences of ISB, 3D positioning precision of joint PPP can be improved by 15%. Compared with joint SPP, the precision difference of joint PPP obtained by the three ISB estimation models is not much obvious. It can also be seen that ISB estimation, when improving the positioning precision, and at the same time increasing the convergence time. Compared with ISB non-estimated processing strategy, the convergence time for ISB estimated strategy has been increased by more than 30% due to the increase of the ISB parameter increase the difficulty of convergence.

Table 3. Comparison of the precision of four ISB estimation methods with PPP

	N/m	E/m	U/m	3D/m	Improvement percentage	Convergence time for 3D/min	Percentage increase in convergence time
No operation	0.183	0.184	0.525	0.586	–	78.5	–
WN	0.175	0.395	0.218	0.484	17%	111.5	30%
PC	0.142	0.330	0.338	0.493	16%	114.5	31%
RW	0.175	0.394	0.214	0.481	18%	112.5	30%

5 Conclusion

ISB between BDS-2 and BDS-3 has an important impact on the positioning precision of Beidou positioning. This paper analyzes the origins of the ISB and compares the three types of ISB estimation model such as white noise model, piecewise constant model, and random walk model. The role of the ISB estimation in improving the precision of the BDS-2 and BDS-3 joint positioning solution are also analyzed. Conclusions of this article are as follows:

(1) For BDS-2 and BDS-3 joint SPP, taking into the account of ISB influence, it can significantly improve the precision of SPP, with the improvement of more than 30%.
(2) For BDS-2 and BDS-3 joint SPP, ISB estimation with random walk model, can obtain better positioning results than white noise model and piecewise constant model.
(3) For BDS-2 and BDS-3 joint PPP, the positioning precision obtained by the three ISB estimation model is comparable.

(4) For BDS-2 and BDS-3 joint PPP, although ISB estimation strategy can improve Beidou positioning precision by more than 10%, it also brings the problem of increased convergence time. How to reduce the increase of convergence time while improving the positioning precision is the content to be studied in the future.

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