BDS Code Bias and Its Effect on Wide Area Differential Service Performance

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Abstract The integrated wide-area differential system of BDS broadcasts differential corrections to compensate broadcast ephemeris errors and enhance user positioning accuracy. It uses real-time pseudo-range observations from ground monitoring stations and calculates differential corrections, which are then broadcasted to users through the GEO satellites. Previous studies show that apparent code biases exist for BDS tracking stations, which in turn will affect the accuracy of differential corrections. This paper analyses the long-term pseudo-range biases based on the residuals in the Precise Orbit Determination (POD), the characteristics of the mean and standard deviation of the pseudo-range bias are studied. A code bias correction model is proposed and applied to BDS wide-area differential calculation. Performance of the code bias model is analysed in real-time pseudo-range based positioning. Results show that: UDRE and user positioning accuracy are improved, where the satellite UDRE is reduced from 0.43 to 0.35 m, and the user positioning accuracy is increased by 10.6% and 14.6% in horizontal and height directions, respectively.

Keywords BDS · Code bias · Differential correction · UDRE · Positioning

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1 Introduction

The BeiDou regional satellite navigation system (BDS) provides legacy PNT service to open users and wide-area differential service to authorized users since October 25, 2012. The BDS satellite constellation is combined of 5 Geostationary Earth Orbit (GEO) satellites, 5 Inclined Geostationary Earth Orbit (IGSO) satellites, and 4 Medium Earth Orbit (MEO) satellites [1–3]. Researches have been carried out in precision orbit determination (POD), precision positioning and wide-area differential positioning [4–8]. Previous researches found the existence of code bias in BDS pseudo-range observations, which is of meter level and is elevation dependent with significant differences between two groups of satellites [9, 10].

As an augmentation service to the legacy navigation message parameters, BDS wide-area differential system calculates the differential corrections using real-time observations of ground monitoring stations. These differential corrections are then broadcasted to the user through the GEO satellites [7, 8]. Since pseudo-range observations are used in the wide-area differential system [8], the code bias will also influence the accuracy of wide-area differential corrections.

In this paper, we analyze the long-term pseudo-range biases based on the residuals in the Precise Orbit Determination (POD). The characteristics of mean and standard deviation of code bias are studied. We developed a code bias correction model. The model is then applied to the estimation of BDS wide-area differential corrections. Real-time pseudo-range observations are used to evaluate the performance of the correction model. Results show that the accuracy of the UDRE and user differential positioning are improved using the code bias correction model, where UDRE is decreased from 0.43 to 0.35 m, and user differential positioning accuracy is increased by 10.6% and 14.6% in the horizontal and height directions respectively.

2 Analysis of BDS Code Bias

Precise orbit determination of BDS makes use of observations of the monitoring stations in China, where the internal 3D precision of the orbit determination is better than 1 m and the radial accuracy of the orbit is better than 0.2 m [6]. The strategies used in BDS POD are shown in Table 1 [6]:

Precise satellite orbits and clocks are the main products in precise orbit determination. Additionally, we can retrieve pseudo-range residuals for each station/satellite pair. Wanninger L et al. [9] analyzed BeiDou code bias derived from BeiDou linear combination observations. In this paper, BeiDou code biases are obtained from POD process. As phase observation has much higher weights in POD, pseudo-range residuals in POD thus reflect the effects of multipath, receiver hardware delays, noise etc., which is used in the next session for code bias analysis and modeling (Table 1).

Table 1 The strategies used in BeiDou precise orbit determination

Items	Description
Arc length	3 days
Data sampling rate	60 s
Estimated solar parameters	Scalar factor and Y-bias
Empirical parameters	Only cosine empirical accelerations in the along-track and cross-track directions to avoid correlation
Troposphere delay factor	One parameter per 4 h
Clock	The master station clock fixed to solve the other clock offsets
Weight rate	Pseudo-range/Phase(1/10000)

2.1 Code Bias Time Series

Based on the pseudo-range residuals from POD in DOY 316–345 of 2016, we calculate the mean and standard deviation of code bias. Figure 1 shows the daily mean and standard deviation of the code bias for each satellite of the station CDJL. We see that the daily mean code bias of different satellites is relatively stable, and they differ among satellites. The code bias standard deviation is stable for most satellites, while the variation of MEO satellites (sat11, sat12, and sat14) is much more obvious with a 7-day period. The variation of daily standard deviation of

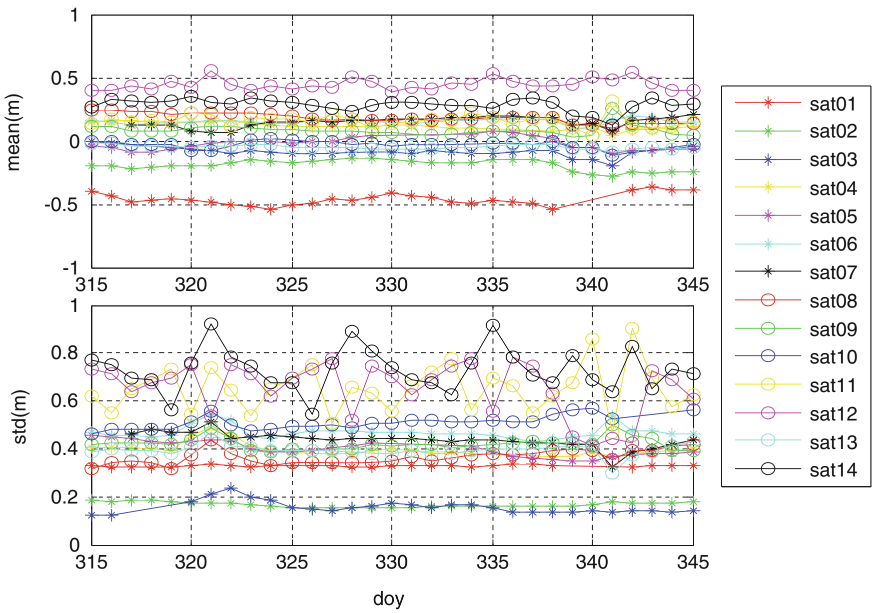

Fig. 1 The daily mean, standard deviation of the pseudo-range residuals

MEO satellites may be due to the different visible MEO arc, while the period of MEO satellite trajectory track relative to the ground station is 7 days.

2.2 Repeatability of Code Bias

Figure 2 shows the daily pseudo-range residual variations for the GEO-02, IGSO-06 and MEO-14 satellites at station BJDN over one-month. The top subplot in (a) shows the time-series of original pseudo-range residuals of GEO-02 for 1 month, where the missing 3 days data is due to satellite maneuvering, and the time-series of the GEO-02 is smoothed over one day and shown in the bottom subplot in (a). Plots (b) and (c) show the original and smoothed residuals of the IGSO/MEO satellites in top and bottom subplots respectively, which show their variation with the elevation angle. In plots (b) and (c), different color curves represent residuals in different days. It is found that the shape of pseudo-range residuals of each satellite is similar and very reproducible. In the range where the satellite elevation angle less than 30°, the satellite pseudo-range bias is relative large, and there is a certain range of tremble accompanied by a large noise. The code bias noise of IGSO/MEO satellites decrease with the elevation angle increase, but the pseudo-range bias still exists, and it is correlated with the satellite elevation angle.

2.3 Code Bias of Different Groups of Satellites

Further analysis of the pseudo-range bias was performed for different groups of satellites, namely the GEO, IGSO, and GEO group. Figure 3 shows pseudo-range residuals of all satellites of the station BJDN in DOY 345 of 2016. It is found that there are differences among different GEO satellites, where the code bias of each

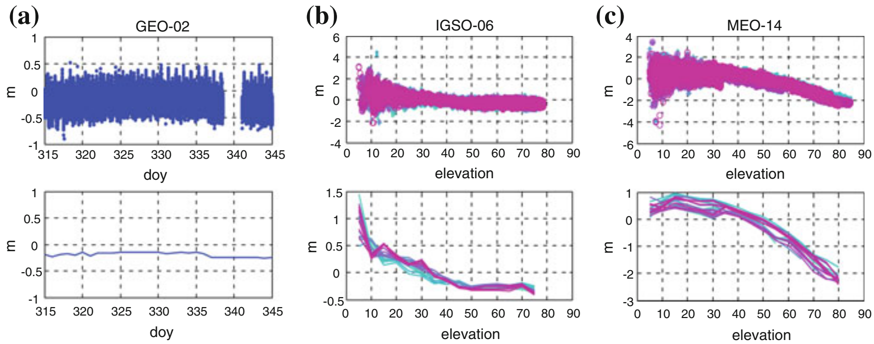

Fig. 2 Pseudo-range residual variations for the GEO-02, IGSO-06 and MEO-14 satellite over one month, where X-axis represents DOY in (**a**); X-axis represents elevation angle in (**b**) and (**c**); *top subplot* represents original pseudo-range residuals, *bottom subplot* represents smoothed pseudo-range residuals, and *different colors* represent different days

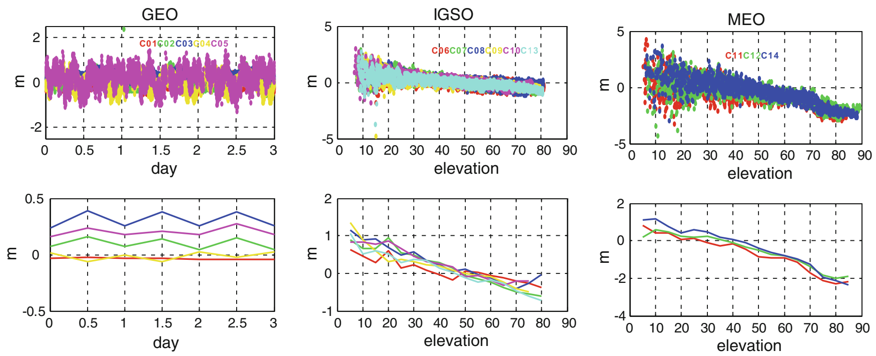

Fig. 3 Code bias of GEO/IGSO/MEO satellites, where *X-axis* represents time in 3 days for GEO; and *X-axis* represents elevation angle for IGSO/MEO; *different colors* represent different satellites

satellite differs in amplitude. The code biases of the same type of MEO or IGSO satellite are more consistent. Furthermore, the code bias of IGSO and MEO satellites differ in the magnitude of pseudo-range bias. The deviation of code bias can reach 1 m between low and high elevation angle. The code bias of IGSO satellite is between 0 and −0.5 m when satellite elevation reaches 90°, while it can reach the amplitude of −2 m for MEO satellite (Fig. 3).

3 BDS Code Bias Correction Model

BeiDou wide-area difference system utilizes the real-time pseudo-range observation of monitoring stations to calculate the wide-area differential correction for users. Based on the above analysis of the BeiDou code bias, we see that code biases are different for satellites at the same station which means that the code bias will not be assimilated in station clock; Also, the code biases are different for stations tracking the same satellite, which means that the code bias will also not be assimilated in satellite clock. Consequently, the code bias will affect the accuracy of wide-area differential corrections.

Wanninger L et al. analyzed BeiDou code bias derived from linear combination observations and set up correction models for BeiDou IGSO/MEO satellites. In this paper, we extend bias modeling for GEO satellites and set the elevation interval to 5° for the piecewise model of IGSO/MEO satellites.

According to the above discussion, the code bias of GEO satellites is long-term stable, constant code bias correction model could be established for GEO represented as Eq. (1):

$$CodeBias_{GEO} = C_i (i = 1, 2, 3, 4, 5) \tag{1}$$

where i denotes satellite PRN number, and C_j is constant term to be determined.

Table 2 Piecewise linear model of Beidou code bias (unit: m)

GEO		IGSO				MEO			
Sat No	Bias	Elevation	Bias	Elevation	Bias	Elevation	Bias	Elevation	Bias
1	−0.052	5	0.838	50	−0.206	5	0.753	50	−0.435
2	0.096	10	0.523	55	−0.216	10	0.488	55	−0.705
3	0.271	15	0.425	60	−0.282	15	0.539	60	−0.825
4	−0.008	20	0.41	65	−0.313	20	0.418	65	−1.01
5	0.176	25	0.355	70	−0.394	25	0.453	70	−1.507
		30	0.295	75	−0.413	30	0.357	75	−1.821
		35	0.162	80	−0.475	35	0.097	80	−2.121
		40	0.065	85	−0.665	40	0.049	85	−2.113
		45	−0.094			45	−0.107		

The code bias of IGSO/MEO satellites is correlated with satellite elevation angle, the correction model of IGSO/MEO satellite could be expressed as piecewise linear function model related to satellite elevation angle shown in Eq. (2):

$$CodeBias_{IGSO/MEO} = \begin{cases} C_j (j < 5) \\ a_j + k_j \cdot (ele - ele_j)\ (j = 5, 10, \ldots, 85) \\ C_j (j > 85) \end{cases} \quad (2)$$

where *ele* is the elevation of the satellite, j represents the elevation angle index of the satellite; and C_j is constant term, a_j, k_j.are model parameters to be estimated.

The model can be provided to the users to interpolate the specific code bias with a given elevation angle.

The BDS code bias correction model is established by above data, and the constant bias value of each GEO satellite and model parameters of IGSO/MEO satellites are shown in Table 2. Figure 4 shows the code biases and their mean value for IGS/MEO satellites at each elevation node.

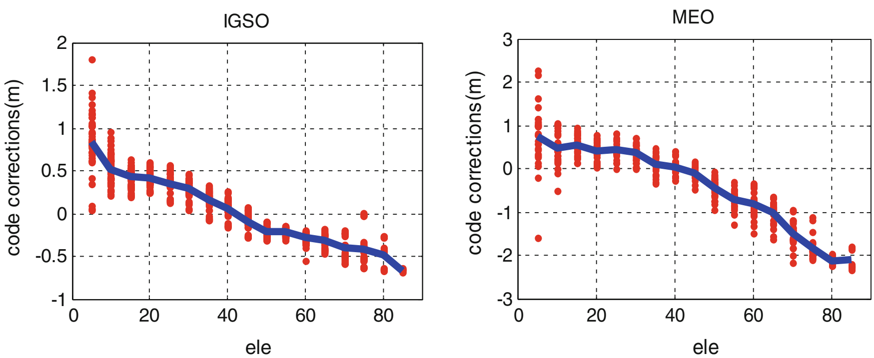

Fig. 4 The bias value of IGSO/MEO satellite at each elevation node, where *X-axis* represents elevation, the *blue* represents the mean bias value at elevation node, the *red* represents value of each satellite

4 Performance Evaluation of Code Bias Model

Applying the BeiDou code bias correction model in the BeiDou wide-area differential correction process, we evaluate the accuracy of resulting differential correction parameters and its performance in user differential positioning. In wide-area differential data processing, same strategies are implemented except the additional code bias model implement.

Experiment was carried out by using observation data in DOY 346 of 2016, two sets of differential corrections (namely "equivalent clock") are calculated with and without code bias corrections. The effect of code bias on differential correction is analyzed and further verified by the user's differential positioning.

4.1 Differences Between the Two Sets of Equivalent Clock

Figure 5 shows two sets of equivalent satellite clock results with and without correcting code bias. GEO-01, IGSO-07 and MEO-14 are analyzed. We found that GEO's equivalent satellite clock differs little with magnitude in 2 dm or less. The equivalent clock difference of IGSO/MEO satellites varies greatly, especially in the low elevation, where the difference may reach 1 m. Table 3 shows the RMS value of the difference for each satellite. It can be seen that the difference of the IGSO/MEO satellite is larger than that of the GEO satellite.

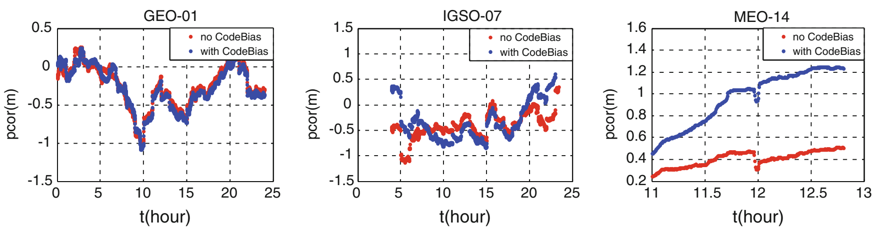

Fig. 5 Differences between the two sets of equivalent clock of C01/C07/C14

Table 3 RMS statistics of satellite equivalent clock differences before and after correction of code bias (unit: m)

satID	RMS	satID	RMS
1	0.066	8	0.336
2	0.044	9	0.337
3	0.029	10	0.34
4	0.022	11	0.332
5	0.135	12	0.327
6	0.35	13	0.34
7	0.356	14	0.59

4.2 UDRE Comparison

The differences between the two sets of equivalent clock may cause difference in the differential positioning accordingly. We calculate the satellite UDRE before and after the application of code bias correction model, and the results are shown in Fig. 6 and Table 4.

In the above figure, satellite 1–5 are GEO satellites, 6–10 and 13 are IGSO satellites, and 11–12 and 14 are MEO satellites. After correcting the code bias model, the GEO satellite UDRE decrease from 0.44 to 0.31 m, the IGSO satellite is from 0.44 to 0.39 m, the MEO satellite is from 0.42 to 0.32 m. The UDRE of all the satellites is improved.

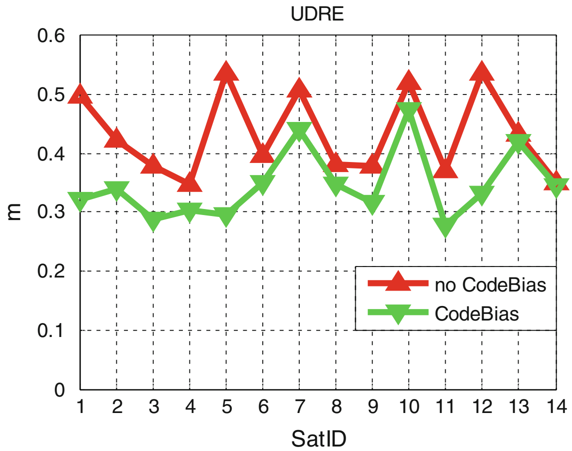

Fig. 6 Satellite UDRE comparison before and after the application of code bias model

Table 4 Satellite UDRE before and after the application of code bias model (unit: m)

satID	UDRE	UDRE (CodeBias)	satID	UDRE	UDRE (CodeBias)
1	0.50	0.32	10	0.52	0.48
2	0.42	0.34	11	0.37	0.28
3	0.38	0.29	12	0.54	0.33
4	0.35	0.30	13	0.43	0.42
5	0.54	0.30	14	0.35	0.35
6	0.40	0.35	GEO	0.44	0.31
7	0.51	0.44	IGSO	0.44	0.39
8	0.38	0.35	MEO	0.42	0.32
9	0.38	0.32	Mean	0.43	0.35

4.3 Comparison of User Differential Positioning Results

Based on the above analysis results, we use two sets of equivalent satellite clock parameters to perform kinematic positioning using dual-frequency pseudo-range data in DOY 346 of 2016. In positioning process, tropospheric delay, solid tide, relativity correction, satellite and receiver phase center offsets were corrected by model.

In the use of equivalent satellite clock parameters with code bias model applied, the same model was used in user station to correct pseudo-range data. Figure 7 shows the results of the two groups of user positioning, where the two sub-graphs show the statistical results of the positioning results of the different stations in the horizontal and height directions, respectively. Table 5 summarized the positioning results, where the user positioning accuracy in the horizontal improves from 1.04 m to 0.93 m, and in height component improves from 1.6 m to 1.36 m. The improvement is about 10.6 and 14.6% for horizontal and height component (Table 5; Fig. 7).

Table 5 The mean statistical results of dual-frequency pseudo-range kinematic differential positioning (unit: m)

	No CodeBias	CodeBias	Improvement percentage
Horizontal	1.036	0.926	10.63
Height	1.597	1.364	14.59

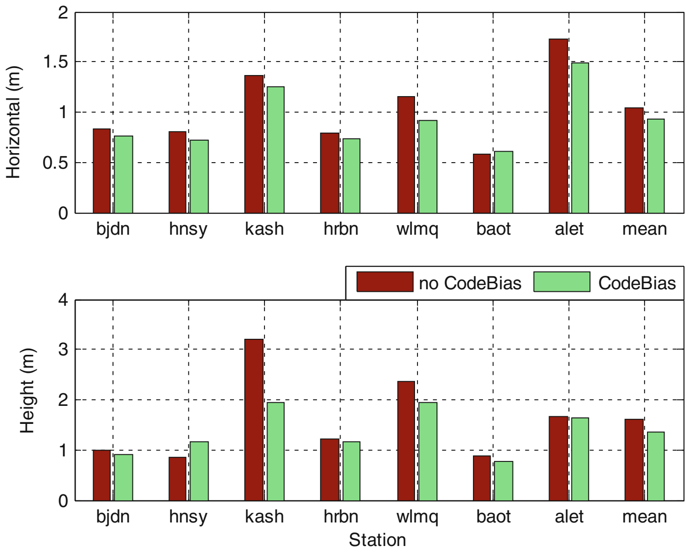

Fig. 7 Comparison of dual-frequency pseudo-range kinematic differential positioning for different stations

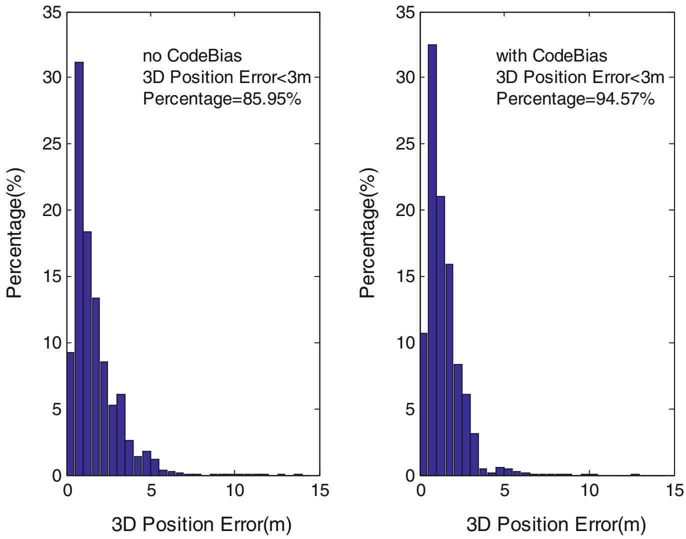

Fig. 8 The histogram of the statistics results of positioning error of all above stations

Figure 8 shows the histogram of the statistics results of positioning error of all above stations. It can be seen that the amount of 3D positioning error bigger than 5 m is reduced, and the percentage of positioning error less than 3 m is increased from 85.9% to 94.5%. This shows that the code bias correction model improves user positioning accuracy and the reliability simultaneously.

5 Conclusion

In this paper, we analyze the long-term pseudo-range residuals results of BeiDou POD. We find that the code bias of GEO satellite is relatively stable, and the code bias of IGSO/MEO satellite is the function of elevation angle. According to the analysis results, the BeiDou code bias correction model is established for different types of satellites, and the model is applied to BeiDou wide area differential processing. The performance of Beidou code bias model is evaluated by using the real-time pseudo-range observations. Results show that UDRE and user positioning accuracy are improved by using the Beidou code bias model, where the satellite UDRE decreased from 0.43 m to 0.35 m, and the user positioning accuracy is improved by 10.6% and 14.6% in horizontal and height directions, respectively.

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