Influence and Correction of Satellite Phase Center Offsets for RNSS Performance of BDS-3

Cheng Liu, Weiguang Gao, Chengpan Tang, and Wei Wang

Abstract BDS-3 provides three kinds of Radio Navigation Satellite Services (RNSS), including primary Positioning Navigation and Timing (PNT), Satellite Based Augmentation System (SBAS) and Precise Point Positioning (PPP). Satellite phase center offsets are important error sources for service performance. Misalignments of frequency-dependent phase centers decrease the service performance further. Therefore, approaches accounting for satellite phase center offsets and the misalignments are prerequisite for satisfactory service performance. Phase center offsets induced errors on ranging and positioning accuracy are analyzed. Different feasible approaches accounting for phase center offsets are presented with reached accuracy. Finally, optimal approaches accounting for the phase center offsets are concluded for all the kinds of RNSS services with real measurements.

Keywords BDS · Satellite phase center offsets · Satellite based augmentation system · Precise point positioning · Total group delay

1 Introduction

On December 27, 2018, the third phase of the BeiDou navigation satellite system (BDS) started providing basic global navigation services, marking the completion of its preliminary system, which consisted of 18 medium Earth orbit (MEO) satellites. BDS-3 is expected to complete the final system—which will consist of three geostationary Earth orbit (GEO) satellites, three inclined geosynchronous orbit (IGSO) satellites, and 24 MEO satellites—and officially provide comprehensive global services by the end of 2020 [1].

C. Liu · W. Gao · W. Wang
Beijing Institute of Tracking and Telecommunication Technology, Beijing, China

C. Tang (✉)
Shanghai Astronomical Observatory, Shanghai, China
e-mail: cptang@shao.ac.cn

Z. Jing and X. Zhan (eds.), *Proceedings of the International Conference on Aerospace System Science and Engineering 2020*, Lecture Notes in Electrical Engineering 680,
https://doi.org/10.1007/978-981-33-6060-0_15

Table 1 Planned open RNSSs to be provided by BDS-3

Service type	Broadcast signals	Broadcasting satellites	Service area	Precision of service (95%)
PNT	B1I, B3I	GEO, IGSO, MEO	Global	Horizontal: 5 m; elevation: 5 m
	B1C, B2a, B2b	GSO, MEO		
SBAS	B1C, B2a	GEO	China and surrounding areas	Meter-level; better than that for basic navigation
PPP	B2b	GEO	China and surrounding areas	Decimeter and centimeter-level for dynamic and static navigation, respectively

The plan is for BDS-3 to provide three types of radio navigation satellite services (RNSSs), namely, basic positioning, navigation, and timing (PNT); satellite-based augmentation system (SBAS) services; and precise point positioning (PPP), as shown in Table 1 [2]. The PNT and SBAS services involve mainly single- or dual-frequency pseudorange measurements [3, 4], whereas the PPP services involve mainly dual-frequency carrier-phase measurements [5–7].

Generally, the satellite antenna phase center (SAPC) and center of mass (CoM) of a navigation satellite do not coincide. Offsets of the SAPC relative to the CoM is referred to as the SAPC offsets [8]. It has been noted that the SAPC offsets of navigation satellites, which can be as large as 2 m, are a major source of navigation and positioning errors and thus must be corrected [8, 9]. To this end, various satellite navigation systems or service organizations have adopted the corresponding countermeasures. Specifically, the Global Positioning System (GPS) of the US and the Quasi-Zenith Satellite System (QZSS) of Japan perform an integrated computation of the satellite orbit and clock error through an ionosphere-free linear combination of the pseudorange and carrier-phase observations at the L1 and L2 frequencies. In other words, the L1/L2 dual-frequency ionosphere-free combination is adopted to compute the virtual SAPC. For the GPS and QZSS, the SAPC serves as the temporal and spatial reference point to define satellite clock errors and generate the satellite broadcast ephemerides, respectively. Furthermore, for the centimeter-level augmentation services of the QZSS, the SAPC serves as the temporal and spatial reference point to define the satellite clock errors and enable precise orbit determination correction, respectively. Thus, the GPS and QZSS require no additional SAPC correction on the user side, making the services easy to use [10]. Similar to the GPS, the Galileo uses a virtual phase center offset (PCO) based on the E1/E5a dual-frequency ionosphere-free combination to generate the freely accessible navigation message (F/NAV). To facilitate interoperability among the global navigation satellite systems (GNSSs), the International GNSS Service (IGS) provides precise ephemerides based on the satellite CoM and the SAPC correction files. To obtain the precision products of the IGS, the user must convert the ephemerides based on the satellite CoM to those based on the SAPC by considering the correction specified in the files [11, 12].

Compared with the GPS, QZSS, and Galileo, the BDS involves a more complex SAPC correction problem that must be resolved [10]. Specifically, the BDS broadcasts the downlink navigation signals at three different frequencies, namely, B1, B2, and B3; however, the SAPC varies with the frequency, leading to different SAPC variations at the three frequencies. In addition, the RNSSs (PNT, SBAS, PPP) provided by the BDS require different levels of precision, and thus, a suitable SAPC correction must be applied for each service by using different methods.

In this work, the influence of the SAPC offsets on the user ranging error and positioning precision of the BDS was theoretically analyzed. Considering the findings, different methods to correct the SAPC variations of the BDS were summarized and described by performing a comparative analysis of the applicability and performance of each approach. Finally, the methods were validated and evaluated using in-orbit observations, and recommendations were made to improve the SAPC correction for the different RNSSs of the BDS.

2 Effect of SAPC Offsets on User Ranging

SAPC variations are fixed with reference to the satellite body, and thus, they can be described using the satellite-fixed coordinate system. The origin (O) of the satellite-fixed coordinate system is the satellite CoM; the Z-axis points to the center of the Earth; the plane XOY is perpendicular to the Z-axis and tangential to the satellite motion trajectory. For the MEO and IGSO satellites of the BDS, the Y-axis is the cross product of the Z-axis and the direction pointing from the satellite to the sun; the X-, Y-, and Z-axes constitute a right-handed coordinate system. For the GEO satellites of the BDS, the Y-axis is the cross product of the Z-axis and the direction of the satellite velocity; in addition, the X-, Y-, and Z-axes constitute a right-handed coordinate system. Generally, the SAPC variation, which is a major source of the user ranging error, is related to the angle between the direction pointing from the satellite to the user and the Z-axis of the satellite-fixed coordinate system, θ, as shown in Fig. 1.

If the SAPC is projected onto the satellite-fixed coordinate system, and the components of the projection on the Z-axis and plane XOY are designated as dz and dxoy, respectively, the component of the projection in the user ranging direction, dr, can be expressed as follows:

$$dr = \cos\theta \cdot dz + \sin\theta \cdot dxoy \tag{1}$$

For the BDS MEO satellites, given the distance between the satellite and the center of the Earth, L ≈ 27,900 km, and the Earth radius R ≈ 6400 km, the maximum and minimum values of θ can be computed as $\theta_{\max} = \arctan\left(\frac{R}{L}\right) = 12.91^\circ$ and $\theta_{min} = 0^\circ$, respectively. Given the range of values of θ, the following equation can be derived:

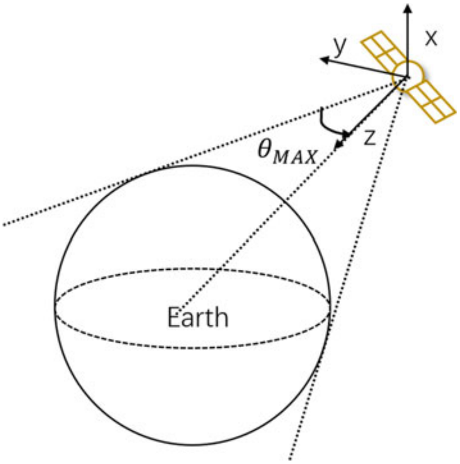

Fig. 1 Schematic of the angle between the direction pointing from the satellite to the center of the Earth and the satellite radial direction [1]

$$dr = (1 \sim 0.975) \cdot dz + (0 \sim 0.223) \cdot dxoy \tag{2}$$

For the GEO and IGSO satellites of the BDS, given the distance between the satellite and the center of the Earth, L ≈ 42,000 km, the maximum and minimum values of θ can be obtained as $\theta_{max} = 12.91°$ and $\theta_{min} = 8.7°$, respectively. Given the range of values of θ, the following equation can be derived:

$$dr = (1 \sim 0.989) \cdot dz + (0 \sim 0.151) \cdot dxoy \tag{3}$$

Equations (2) and (3) show that the component of the projection of the SAPC on the Z-axis, dz, is the major source of the user equivalent range error (UERE). Thus, when the direction of the vector of the SAPC offsets approximate that of the Z-axis of the satellite-fixed coordinate system, the SAPC offset considerably influences the UERE, with the maximum influence equal to the absolute value of the SAPC offset (up to 2 m, as mentioned previously). In addition, if the multiple-frequency signals of the BDS are combined to realize navigation and positioning, the presence of frequency-specific SAPC variations is expected to further increase the UERE.

In summary, the impact of the SAPC variations cannot be neglected even for the PNT services with meter-level precision, because the presence of SAPC variations can lead to a maximum UERE of several meters. For the SBAS, PPP, and other augmentation services, it is critical to reasonably and effectively correct the SAPC variations.

3 Methods to Correct the BDS SAPC Variations and Comparative Analysis

3.1 SAPC Orbit Broadcast-Based Correction Methods

Full correction model. The SAPC variations can be corrected based on the SAPC orbital parameters. In this method, the ground operation control system (GOCS) computes the SAPC-referenced orbital parameters and uploads them onto the satellite to broadcast the ephemeris.

Specifically, first, the GOCS performs dynamic and static orbit determination based on observations, thereby obtaining the CoM-referenced numerical orbit of the navigation satellite [13]. Subsequently, the SAPC offsets vector in the satellite-fixed coordinate system, $[dx_{\text{phs}} \quad dy_{\text{phs}} \quad dz_{\text{phs}}]^{\text{T}}$, is transformed into a vector in the Earth-centered Earth-fixed coordinate system (ECEF) by using the following equation [13]:

$$\begin{bmatrix} dx_{\text{ECEF}} \\ dy_{\text{ECEF}} \\ dz_{\text{ECEF}} \end{bmatrix} = \boldsymbol{R}_{\text{ciscts}} \cdot [\boldsymbol{e}_x \quad \boldsymbol{e}_y \quad \boldsymbol{e}_z] \cdot \begin{bmatrix} dx_{\text{phs}} \\ dy_{\text{phs}} \\ dz_{\text{phs}} \end{bmatrix} \tag{4}$$

where $[dx_{\text{ECEF}} \quad dy_{\text{ECEF}} \quad dz_{\text{ECEF}}]^{\text{T}}$ is the SAPC offsets vector in the ECEF; $\boldsymbol{R}_{\text{ciscts}}$ is the rotation matrix for the transformation between the satellite-fixed inertial coordinate system and the ECEF; and $[\boldsymbol{e}_x \quad \boldsymbol{e}_y \quad \boldsymbol{e}_z]$ is the vector of the satellite-fixed coordinate system, which is related to the satellite attitude.

The satellite orbits in reference to the SAPC at different frequencies can be obtained by superimposing the SAPC offsets vector in the ECEF, $[dx_{\text{ECEF}} \quad dy_{\text{ECEF}} \quad dz_{\text{ECEF}}]^{\text{T}}$, onto the satellite CoM numerical orbit. The GOCS generates the ephemerides to be broadcast by using the SAPC-referenced orbits [14] and uploads the ephemerides onto the satellite to be broadcasted.

The GPS and QZSS have already adopted this method, and this approach is applicable to the BDS, albeit with certain minor modifications. First, the numerical orbits in reference to the SAPC at different frequencies (B1, B2, and B3) need to be converted into separate broadcast ephemerides, which are later uploaded onto the satellite, to be broadcasted.

In addition, for the BDS, the vector of the satellite-fixed coordinate system, $[\boldsymbol{e}_x \quad \boldsymbol{e}_y \quad \boldsymbol{e}_z]$, needs to be computed using different methods for satellites having different types of orbits. In particular, for the MEO and IGSO satellites, the reference coordinate system under the yaw-steering mode can be expressed as follows:

$$\begin{cases} \boldsymbol{e}_z = -\dfrac{\boldsymbol{r}}{|\boldsymbol{r}|} \\ \boldsymbol{e}_y = \boldsymbol{e}_z \times \dfrac{\boldsymbol{r}_{\text{sun}} - \boldsymbol{r}}{|\boldsymbol{r}_{\text{sun}} - \boldsymbol{r}|} \\ \boldsymbol{e}_x = \boldsymbol{e}_y \times \boldsymbol{e}_z \end{cases} \tag{5}$$

where r and r_{sun} denote the position vectors of the satellite and the sun in the inertial coordinate system, respectively. For the GEO satellites, the reference coordinate system under the orbit-normal mode can be expressed as follows:

$$\begin{cases} \boldsymbol{e}_z = -\dfrac{\boldsymbol{r}}{|\boldsymbol{r}|} \\ \boldsymbol{e}_y = \boldsymbol{e}_z \times \dfrac{\boldsymbol{v}}{|\boldsymbol{v}|} \\ \boldsymbol{e}_x = \boldsymbol{e}_y \times \boldsymbol{e}_z \end{cases} \tag{6}$$

where v is the satellite velocity vector in the satellite-fixed inertial coordinate system.

In this method, the SAPC serves as both the spatial and temporal reference points for the navigation satellite broadcast ephemeris and satellite clock error, respectively. The advantages of this method are that the SAPC variations in the broadcast ephemerides exhibit nearly no precision loss, and no additional corrections are required on the user side. However, broadcasting the ephemerides in reference to the SAPC at different frequencies requires a simultaneous upload of several sets of navigation messages from the GOCS to the satellite, thereby significantly increasing the message transmission load on the GOCS, which is the most notable limitation in the application of this approach to the BDS.

Group delay-based correction model. To reduce the computation and message transmission load on the GOCS in the full correction model, the BDS can broadcast the satellite navigation messages for the reference frequency and use the group delay to correct the SAPC offsets at the other frequencies relative to that at the reference frequency.

Equations (1) to (3) show that the component of the projection of the SAPC offsets on the Z-axis, *dz*, is the major source of the ranging error, whereas the component of the projection on the plane *XOY*, *dxoy*, exerts only a relatively small impact on the ranging error. Thus, to reduce the computation and processing load on the system and user receivers, a straightforward implementation of the aforementioned full correction model involves broadcasting the component of the SAPC projection on only the Z-axis.

Specifically, only the broadcast ephemeris in reference to the SAPC at a single frequency (the reference frequency) is uploaded onto the satellite for broadcasting. The component of the projection of the SAPC offsets at the other frequencies relative to that at the reference frequency on the Z-axis (the direction pointing from the satellite to the center of the Earth) is approximated and corrected using the group delay, as shown in Fig. 2 (where c is the speed of light).

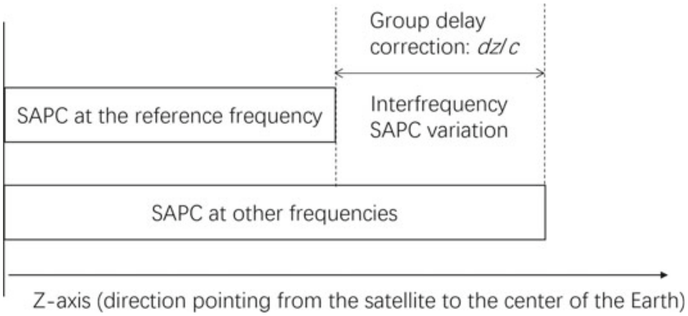

Fig. 2 Schematic of group delay-based SAPC correction model [2]

Consequently, the broadcast ephemerides for the signals at the different frequencies have the same satellite orbit and clock error, and the only difference is in terms of the parametric values for the signal group delay, thereby considerably reducing the uplink data transmission load on the GOCS.

3.2 Satellite CoM Orbit Broadcast-Based Correction Methods

Correction model based on the conversion of the satellite CoM to the SAPC. The SAPC can be corrected by converting the satellite CoM to the SAPC. In particular, the GOCS uploads the CoM-based broadcast ephemerides. The three-axial variations of the SAPC relative to the satellite CoM are provided to the user through a separate means of communication (for example, the internet). Subsequently, the corresponding vector corrections to the CoM are implemented using the method described in Sect. 3.1, thereby correcting the SAPC. This method reduces the computation and communication load on the GOCS; however, it increases the computation and communication load on the user side.

Satellite clock error and group delay-based correction model. The correction model based on the conversion of the satellite CoM to the SAPC can offset the impact of the SAPC offsets with almost no precision loss. However, the parametric settings to convert the satellite CoM to the SAPC for each satellite must be provided to the user through a separate means of communication (for example, the internet), thereby reducing the ease of use of the approach. To simplify the system broadcast and process flow, on the premise of broadcasting the satellite CoM-based orbital parameters, the SAPC can be corrected using the satellite clock error and group delay.

Specifically, first, the SAPC offsets at the reference frequency is approximated and expressed in terms of the satellite clock error a_0. Next, the SAPC offsets at the other frequencies relative to that at the reference frequency is approximated and expressed using the group delay.

Subsequently, the SAPC correction for the reference frequency in the direction from the satellite to a given ground observation station P (with known coordinates) in the service area, $d\rho_{phs}$, can be computed using the following equation, based on observations at a predefined sampling interval:

$$\mathrm{d}\rho_{phs} = \begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix}^T \cdot \frac{\boldsymbol{r}_{sta} - \boldsymbol{r}}{|\boldsymbol{r}_{sta} - \boldsymbol{r}|} \tag{7}$$

where r_{sta} and r are the position vectors of the ground observation station P and the satellite in the ECEF, respectively. Considering the multiple samples collected at a predefined sampling interval for a given period and the $d\rho_{phs}$ value computed for each sample, the statistical mean of the $d\rho_{phs}$ values, Δa_0, can be used as the SAPC correction:

$$\Delta a_0 = \frac{\sum_{i=1}^{n} d\rho_{phs}}{c * n} \tag{8}$$

where c is the speed of light ($c = 3 \times 10^8$ m/s); and n is the number of observation samples collected in the observation period for the SAPC correction. The SAPC correction for the service area can be realized by correcting the satellite clock error (a_0) by using the resulting Δ_{a0} value.

This method uses the satellite clock error to approximate the SAPC offsets at the reference frequency; however, the projection of this offsets in the direction of the Earth may change. Therefore, the precision of this method depends on the anisotropy of the projection of the SAPC offsets at the reference frequency. In addition, because the SAPC offsets at the other frequencies relative to that at the reference frequency is approximated using the group delay, the precision of this method depends on the anisotropy of the projection of the frequency-specific SAPC variation.

3.3 Comparative Analysis of the Methods

Precision of correction. The difference in the precision values of the aforementioned SAPC correction methods can be attributed to the fact that the approaches neglect the anisotropy of the SAPC to different extents. Specifically, although the full correction model realizes a full correction of the SAPC, the satellite CoM-SAPC conversion-based correction model provides the user with the relationship to convert the satellite CoM orbit to the SAPC orbits at different frequencies. However, both the methods consider the anisotropy of the SAPC and can thus correct the SAPC offsets with almost no precision loss.

In contrast, the group delay-based correction model considers the anisotropy of the SAPC offsets at the reference frequency (B3) but neglects the anisotropy of the frequency-specific SAPC variations. The maximum projection of the frequency-specific SAPC variations in the pseudorange direction can be expressed as follows:

$$\max\_\mathrm{diff}\, dr = |\cos\theta_{\max} - \cos\theta_{\min}| \cdot dz + |\sin\theta_{\max} - \sin\theta_{\min}| \cdot dxoy \tag{9}$$

For the MEO satellites, Eq. (9) can be rewritten as follows:

$$\max\_\mathrm{diff}\, dr = 0.025 \cdot dz + 0.223 \cdot dxoy \tag{10}$$

For the GEO and IGSO satellites, Eq. (9) can be rewritten as follows:

$$\max\_\mathrm{diff}\, dr = 0.011 \cdot dz + 0.151 \cdot dxoy \tag{11}$$

For the BDS, if the Z-axis component of the frequency-specific SAPC offset is 0.3 m, and the component in the plane *XOY* is 0.02 m, the anisotropy of the projection of the frequency-specific SAPC offsets is 0.006 m for the GEO and IGSO satellites and 0.012 m for the MEO satellites.

The satellite clock error and group delay-based correction model is based on the group delay-based correction model; however, the satellite clock error is used instead of the broadcast ephemeris to approximate and express the SAPC offsets at the reference frequency. Therefore, the precision of this method depends on the anisotropy of the projection of the SAPC offsets at the reference frequency as well as that of the frequency-specific SAPC variation. Consequently, this approach involves the largest precision loss. Equation (1) shows that the direction of projection of a satellite varies with the location of the ground users; thus, the user ranging error caused by the SAPC offsets also varies.

Generally, the components of the projection of the SAPC offsets on the Z-axis, *dz*, and that in the plane *XOY*, *dxoy*, have a maximum value of approximately 1 m and several decimeters, respectively. If $dz = 1.0$ m, and $dxoy = 0.6$ m, the offsets in the ranging error caused by the SAPC offsets at the reference frequency for different ground users can reach 0.15 m for the MEO satellites of the BDS and 0.11 m for the GEO and IGSO satellites.

Table 2 lists the estimated precision losses of the different correction models.

Uplink load and user friendliness. Among the four methods of correction, the full correction model exerts the largest uplink load on the GOCS. In particular, for the BDS, this method requires the generation and upload of the navigation messages for the SAPC variations at all the three frequencies (B1, B2, and B3). The group delay-based correction model and the satellite clock error and group delay-based correction model exert the smallest uplink loads, because the navigation messages for the different frequencies are different only in terms of the satellite clock error and group delay. The correction model based on the conversion of the satellite CoM to the SAPC requires the uploading of only one set of navigation messages; however,

Table 2 Estimated precision losses of different correction models (unit: m)

Source of precision loss	Correction based on SAPC orbit broadcast		Correction based on satellite CoM orbit broadcast	
	Full correction model	Group delay-based correction model	Correction model based on the conversion of the satellite CoM to the SAPC	Satellite clock error and group delay-based correction model
Anisotropy of the projection of the SAPC offsets at the reference frequency	0	0	0	0.11–0.15
Anisotropy of the frequency-specific SAPC variation	0	0.006–0.012	0	0.006–0.012

the relationship to convert the satellite CoM to the SAPC must be provided to the user through a separate means of communication, thereby increasing the load on the GOCS.

In terms of user experience, the full correction model, group delay-based correction model, and satellite clock error and group delay-based correction model provide SAPC corrections that are not provided to the user, requiring no additional corrections on the user side. In comparison, the correction model based on the conversion of the satellite CoM to the SAPC requires the user to receive parameters or files to convert the satellite CoM to the SAPC and is thus more complex to use.

Lateral comparison. Table 3 summarizes the comparative analysis results of the correction models in terms of their precision, uplink load on the ground system, and user friendliness.

4 Test and Validation

4.1 Anisotropy of the Ranging Error Induced by the SAPC Offsets at the Reference Frequency

The anisotropy of the ranging error induced by the SAPC offsets at the reference frequency impacts the precision of the satellite clock error and group delay-based correction model.

This anisotropy for a BDS MEO satellite was computed using the ranging errors for five observation stations located in North, Northeast, Northwest, Southwest, and South China, with the results shown in Fig. 3. The maximum offsets in the anisotropy

Table 3 Comparison of the performance of the correction models

Performance parameter	Correction based on SAPC orbit broadcast		Correction based on satellite CoM orbit broadcast	
	Full correction model	Group delay-based correction model	Correction model based on the conversion of the satellite CoM to the SAPC	Satellite clock error and group delay-based correction model
Precision of correction	High	Average	High	Low
Uplink load on the ground system	High	Low	Average	Low
User friendliness	High	High	Low	High

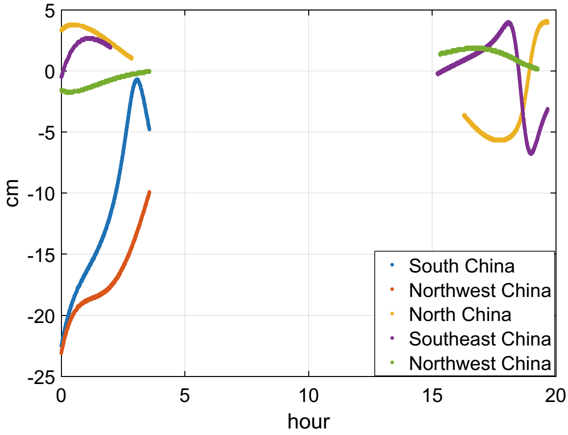

Fig. 3 Anisotropy of the projection of the SAPC offsets at the reference frequency of a BDS MEO satellite [3]

of the ranging error was 25 cm, which is consistent with the theoretical estimation presented in previous sections.

4.2 *Anisotropy of the Projection of the Frequency-Specific SAPC Variation*

The anisotropy of the projection of the frequency-specific SAPC offsets impacts the precision of the group delay-based correction model and the satellite clock error and group-delay-based correction model.

Figures 4, 5, and 6 show the anisotropies of the projection of the B1/B3

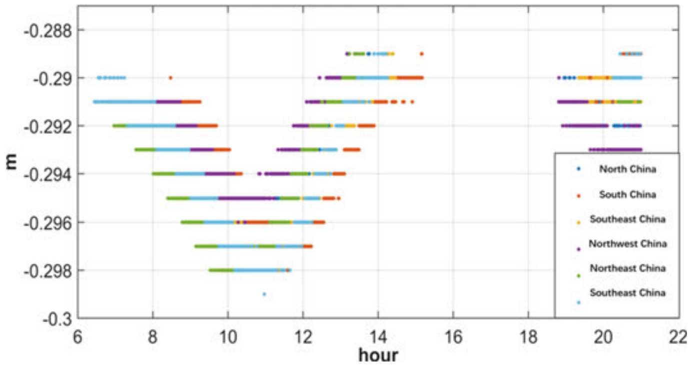

Fig. 4 Anisotropy of the projection of the B1/B3 frequency-specific SAPC offsets differences of a BDS MEO satellite [4]

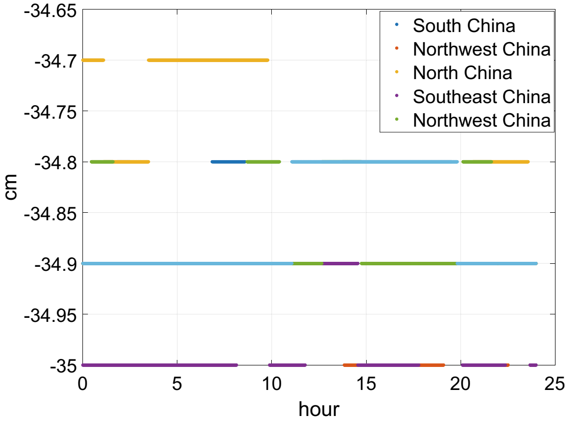

Fig. 5 Anisotropy of the projection of the B1/B3 frequency-specific SAPC offsets differences of a BDS GEO satellite [5]

frequency-specific SAPC offsets of the MEO, GEO, and IGSO satellites of the BDS, respectively.

The maximum offsets in the anisotropy of the projection of the frequency-specific SAPC offsets was 1 cm for the MEO and IGSO satellites, which is of the same order of magnitude as the theoretical estimation presented in Sect. 3.3. An error of this order of magnitude cannot be neglected for the PPP and PPP/RTK services.

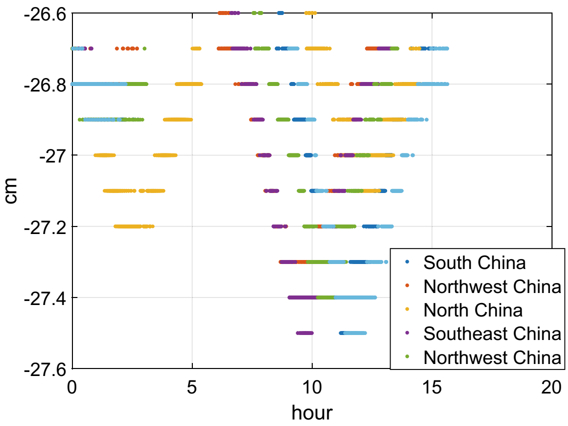

Fig. 6 Anisotropy of the projection of the B1/B3 frequency-specific SAPC offsets differences of a BDS IGSO satellite [6]

4.3 *Impact of the Different SAPC Correction Methods on the Positioning Precision of the BDS*

Impact on the PNT services. The observations obtained from five ground observation stations located in China during the period of November 1–10, 2019 were used to evaluate the BI/B3I dual-frequency PNT in the context of different SAPC correction methods. The results are summarized in Table 4.

Table 4 Errors in the BDS PNT generated when using different SAPC correction models (95%; unit: m)

Observation station	No SAPC correction	Correction based on SAPC orbit broadcast		Correction based on satellite CoM orbit broadcast	
		Full correction model	Group delay-based correction model	Correction model based on the conversion of the satellite CoM to the SAPC	Satellite clock error and group delay-based correction model
bjf1	3.89	3.10	3.12	3.10	3.39
chu1	4.12	3.46	3.47	3.46	3.71
gua1	3.11	2.00	1.99	2.00	2.13
kun1	2.96	1.67	1.68	1.67	2.17
xia1	3.67	2.79	2.76	2.79	2.84
Mean	3.55	2.60	2.60	2.60	2.85

The error in the BDS PNT caused by the SAPC offsets was approximately 1 m for the five ground observation stations. Thus, correcting the SAPC is necessary for the meter-level-precision PNT services. Although the four correction methods have different levels of precision performance, the values are acceptable for the PNT services. The full correction model and the correction model based on the conversion of the satellite CoM to the SAPC exhibited the highest precision, followed by those of the group delay-based model and the satellite clock error and group delay-based model.

Impact on the SBAS services. The observations obtained from five ground observation stations located in China during the period of November 1–10, 2019 were used to evaluate BI/B3I dual-frequency augmented positioning when using the different SAPC correction methods. The results are summarized in Table 5.

The errors in the BDS SBAS positioning generated owing to the SAPC variations are more than 1 m for the five ground observation stations. Thus, correcting the SAPC is necessary for the meter-level-precision SBAS positioning services. As in the case of the PNT services, although the four correction methods exhibit different levels of precision performance, the values are acceptable for the SBAS positioning services. Specifically, the full correction model and the correction model based on the conversion of the satellite CoM to the SAPC exhibit the highest precision, followed by those of the group delay-based model and the satellite clock error and group delay-based model.

Impact on the PPP services. The observations obtained from five ground monitoring stations located in China during the period of November 1–10, 2019 were used to evaluate the BI/B3I dual-frequency PPP services when using the different SAPC correction methods, and the results are summarized in Table 6. In the computation,

Table 5 Errors in BDS SBAS positioning when using different SAPC correction methods (95%; unit: m)

Observation station	No SAPC correction	Correction based on SAPC orbit broadcast		Correction based on satellite CoM orbit broadcast	
		Full correction model	Group delay-based correction model	Correction model based on the conversion of the satellite CoM to the SAPC	Satellite clock error and group delay-based correction model
bjf1	3.24	2.10	2.13	2.10	2.22
chu1	3.42	2.74	2.77	2.74	2.81
gua1	2.76	1.84	1.88	1.84	1.96
kun1	2.12	1.55	1.60	1.55	1.70
xia1	3.01	2.41	2.43	2.41	2.55
Mean	2.91	2.13	2.16	2.13	2.25

Table 6 Errors in BDS PPP positioning when using different SAPC correction models (95%; unit: m)

Observation station	No SAPC correction	Correction based on SAPC orbit broadcast		Correction based on satellite CoM orbit broadcast	
		Full correction model	Group delay-based correction model	Correction model based on the conversion of the satellite CoM to the SAPC	Satellite clock error and group delay-based correction model
bjf1	10.3	1.0	2.0	1.0	4.0
chu1	9.5	1.4	1.9	1.4	5.1
gua1	11.4	1.6	2.4	1.6	3.9
kun1	8.5	0.9	3.0	0.9	4.5
xia1	6.9	1.2	2.3	1.2	5.2
Mean	9.3	1.2	2.3	1.2	4.5

the satellite precision ephemeris and clock error were based on the satellite station and intersatellite combined orbit determination, respectively.

The maximum errors in the BDS PPP positioning generated owing to the SAPC variations for the five ground observation stations are approximately 10 cm. Thus, SAPC correction is necessary. The full correction model and the correction model based on the conversion of the satellite CoM to the SAPC exhibit the highest precision. The group delay-based correction model involved an additional precision loss of approximately 1–2 cm, and the satellite clock error and group-delay-based correction model had a further precision loss of approximately 2–3 cm. Thus, for the PPP and PPP-RTK services with centimeter-level precision, the SAPC should be corrected with discretion.

5 Conclusion

The plan for the BDS-3 is to provide three types of open RNSSs (PNT, SBAS, and PPP). However, the offsets in the SAPC is a major source of error of the BDS RNSSs and thus must be corrected. The SAPC of the BDS navigation satellites varies with the frequency. Thus, both the SAPC offsets at the reference frequency and the frequency-specific SAPC offsets must be corrected when applying the BDS RNSSs, which is a unique challenge that does not occur in the case of the GPS and QZSS.

In this study, the impact of the SAPC offsets on the user ranging and positioning precision of the BDS was theoretically analyzed. Considering the findings, methods to correct the SAPC offsets of the BDS, including the method currently used by the BDS system, that is, the group delay-based method, were summarized and described. Subsequently, the methods were comprehensively compared in terms of the precision of correction, uplink load on the ground system, and user friendliness. Finally, the performance of the methods was evaluated by using BDS observations, thereby validating the effectiveness of the methods and confirming the results of the theoretical analysis.

Overall, the SAPC correction currently used by the BDS, that is, the group delay-based correction, is acceptable for the PNT and SBAS services, as it does not involve a significant precision loss. However, for the BDS PPP services, which require a centimeter-level precision, the currently used SAPC correction must be improved and upgraded. The satellite CoM expression-based SAPC correction results in a precision loss for the BDS PNT and SBAS services, and thus, the navigation message generation strategy currently used by the BDS GOCS must be modified. Thus, we propose the SAPC correction to be upgraded based on the SAPC expression. Specifically, we recommend that the uplink processing capacity of the GOCS is increased to realize the upload of multiple-frequency navigation messages, thereby allowing the adoption of the full correction model. If the currently used group delay-based correction must be retained, we recommend the additional correction of the frequency-specific SAPC offsets for the PPP services and the provision of the corrections to the users through navigation message broadcasting or the internet.

Acknowledgements The project is supported by National Natural Science Foundation of China (Grant Nos. 42074044, 41874039, and 41804030).

References

1. Development of the BeiDou navigation satellite system (Version 4.0). China Satellite Navigation Office, Dec 2019
2. BeiDou navigation satellite system open service performance standard (Version 2.0). China Satellite Navigation Office, Dec 2018
3. SBAS IWG (2016) Satellite-based augmentation system dual-frequency multi-constellation definition document. SBAS IWG 31, Senegal, 29 Nov–1 Dec 2016
4. SBAS IWG (2016) SBAS L5 DFMC interface control. In: SBAS IWG 31, Senegal, 29 Nov–1 Dec 2016
5. Yang Y, Xu Y, Li J et al (2018) Progress and expected performance of the BeiDou-3 system: analysis of test validation data. Sci Sin (Terrae) 48(5):584–594 (in Chinese)
6. Guo S, Cai H, Meng Y et al (2019) BDS-3 RNSS technical characteristics and service performance. Acta Geod Cartograph Sin 48(7):810–821 (in Chinese with English abstract)
7. Yang Y, Gao W, Guo S et al (2019) Introduction to BeiDou-3 navigation satellite system. Navigation 66(1):7–18
8. Montenbruck O, Schmid R, Mercier F et al (2015) GNSS satellite geometry and attitude models. Adv Space Res 56(6):1015–1029
9. Dilssner F, Springer T, Schönemann E et al (2014) Estimation of satellite antenna phase center corrections for BeiDou. In: IGS workshop, pp 23–27. MLA
10. Bertiger W, Bar-Sever Y, Harvey NK et al (2010) Next generation GPS ground control segment (OCX) navigation design. In: Institute of navigation GNSS meeting, Portland, OR, Sept 2010
11. Dow JM, Neilan RE, Rizos C (2009) The international GNSS service: in a changing landscape of global navigation satellite systems. J Geod 83:191–198

12. Kouba J, Héroux P (2001) Precise point positioning using IGS orbit and clock products. GPS Solut 5(2):12–28
13. Schutz B, Tapley B, Born GH (2004) Statistical orbit determination. Elsevier
14. Cui X, Jiao W, Jia X et al (2004) The fitting algorithm of GPS broadcast ephemeris parameters. J Inst Surv Map (J Geomatics Sci Technol) 21(4):244–246 (in Chinese with English abstract)