Research on Accuracy Estimation Methods for BeiDou Coordinate Frame (Postprint)

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Abstract

From the perspective of RNSS (radio navigation satellite system) meter-level service, this paper presents estimation methods for the realization accuracy of BDCS (Beidou coordinate system), including the broadcast ephemeris positioning method, the precise ephemeris versus broadcast ephemeris comparison method, and the satellite laser ranging (SLR) coordinate estimation method. The broadcast ephemeris positioning method is suitable for users' real-time monitoring of reference frame realization accuracy, but its monitoring accuracy is limited by the accuracy of the broadcast ephemeris. The orbit comparison method introduces post-processed precise products, offering relatively high monitoring accuracy, but its timeliness is relatively poor. The SLR coordinate estimation method is not affected by ionospheric delay and satellite clock bias, achieving the highest accuracy among the three methods, but due to the limited amount of laser ranging data, it cannot be used for short-term monitoring. The results show that all three methods estimate the alignment accuracy between BDCS and ITRF to be at the centimeter level. Finally, against the backdrop of China-Russia satellite navigation system cooperation, the alignment accuracy between BDCS and PZ-90 is estimated, with results indicating that the two systems are aligned at the centimeter level, which can meet the application requirements of meter-level positioning users. With the improvement of BDS-3 broadcast ephemeris accuracy and the development of SLR, the estimation accuracy of the aforementioned three methods will be further enhanced.

Full Text

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Abstract

From the perspective of RNSS (Radio Navigation Satellite System) meter-level services, this paper presents accuracy evaluation methods for the BDCS (BeiDou Coordinate System) implementation, including the broadcast ephemeris positioning method, precise ephemeris versus broadcast ephemeris comparison method, and satellite laser ranging (SLR) coordinate estimation method. The broadcast ephemeris positioning method enables real-time monitoring of reference frame implementation accuracy for users, though its monitoring precision is limited by broadcast ephemeris accuracy. The ephemeris comparison method incorporates post-processed precise products, achieving higher monitoring accuracy but with relatively poor timeliness. The SLR coordinate estimation method is least affected by ionospheric delay and is unaffected by satellite clock errors, yielding the highest precision among the three methods; however, due to limited laser ranging data volume, it cannot support short-term monitoring. Results demonstrate that all three methods estimate BDCS-ITRF alignment accuracy at the centimeter level. Finally, against the backdrop of Sino-Russian satellite navigation system cooperation, the alignment accuracy between BDCS and PZ-90 was evaluated, showing centimeter-level alignment that satisfies meter-level positioning user application requirements. With improvements in BeiDou-3 broadcast ephemeris precision and SLR development, the evaluation accuracy of these three methods will further increase.

Keywords: BeiDou Coordinate System; broadcast ephemeris positioning; satellite laser ranging; accuracy monitoring

1 Introduction

The International Terrestrial Reference Frame (ITRF) is the realization of the International Terrestrial Reference System (ITRS), established and maintained through four space geodetic techniques: Global Navigation Satellite System (GNSS), Very Long Baseline Interferometry (VLBI), SLR, and Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS). The latest version, ITRF2014, was released in January 2016 [1–3].

Different navigation systems employ different spatial datums. For instance, GPS uses the WGS84 coordinate system, GLONASS uses PZ-90, and Galileo uses GTRF. To ensure compatibility and interoperability among satellite navigation systems, current navigation system reference frames achieve consistency by aligning with ITRF. Two methods can estimate navigation system reference frame accuracy: (1) directly calculating transformation parameters using precise coordinates of ground stations in two reference frames, and (2) indirectly monitoring and estimating frame alignment accuracy through satellite orbit products and positioning results containing coordinate frame information. Navigation system providers typically use the first method to obtain precise alignment estimates with ITRF, which requires monitoring station data used during reference frame implementation—data generally unavailable to users. For user monitoring of navigation system reference frame accuracy, the second method is generally adopted, i.e., indirect estimation through broadcast ephemeris and other products. These methods differ in monitoring precision and timeliness: the first achieves millimeter-level precision estimation, typically used during frame implementation, while the second, though less precise, facilitates user monitoring and estimation of reference frame accuracy. This paper focuses on analyzing the estimation precision of the second method and evaluates BDCS using measured data [4].

The spatial datum of the BeiDou Satellite Navigation System is the BeiDou Coordinate System. BDCS utilizes observation data from over 120 GNSS monitoring stations distributed across China and globally to achieve alignment with ITRF2014. The latest BDCS version achieves millimeter-level alignment with ITRF2014 through IGS monitoring stations.

In addition to the accuracy of navigation system reference frames published by providers, IGS also provides GPS spatial datum accuracy monitoring results from a user perspective. IGS monitors spatial datum alignment accuracy by comparing GPS broadcast ephemeris with IGS rapid ephemeris products to calculate seven parameters, representing to some extent the spatial datum transfer precision from GPS satellites to RNSS users [5–7].

This paper analyzes the estimation accuracy of the aforementioned methods. Considering the high precision of BDS-3 navigation message orbits and the fact that all satellites carry laser retroreflectors, we propose using broadcast ephemeris positioning and SLR coordinate methods to estimate BDS spatial datum transfer precision. Against the backdrop of Sino-Russian spatial datum interoperability applications, we also use the SLR method to estimate alignment accuracy between BDS and GLONASS systems, providing support for navigation system compatibility and interoperability.

2.1 Broadcast Ephemeris Positioning Method

The broadcast ephemeris positioning method fixes satellite orbits and clock errors from broadcast ephemeris to estimate daily position parameters for GNSS monitoring stations, receiver clock errors at each epoch, atmospheric refraction errors every 6 hours, and phase ambiguities. The observation equation is:

$$PC_i = \rho + c(t_r + t_s) + d_{trop} + d_{other}$$
$$LC_i = \rho + c(t_r + t_s) + d_{trop} + \lambda_i + N_i + d_{other}$$

where PC_i is the ionosphere-free pseudorange combination, LC_i is the ionosphere-free carrier phase combination, ρ is the geometric distance between satellite and receiver, t_r and t_s are receiver and satellite clock errors respectively, d_{trop} is tropospheric delay, d_{other} represents other error terms such as relativistic effects, solid Earth and ocean tide corrections, and multipath noise, λ_i is the ionosphere-free combination wavelength, N_i is the combined ambiguity unknown, and c is the speed of light ($c = 299,792,458\,\mathrm{m/s}$). To achieve real-time monitoring of navigation system spatial datum transfer, this method uses broadcast ephemeris to calculate satellite orbits and clock errors at each epoch.

Using one-day arc observations from IGS stations, coordinate parameters are solved to obtain monitoring station coordinates in the navigation system reference frame. These coordinates, together with the station coordinates in ITRF2014, are used to estimate transformation parameters, yielding translation, rotation, and scale factor parameters of the reference frame relative to ITRF2014. The seven-parameter transformation formula is:

$$X_{GNSS} = X_{trans} + (1 + X_{scale}) \times X_{rot} \times X_{ITRF}$$

where X_{trans} represents translation parameters, X_{rot} rotation parameters, X_{scale} scale factor, X_{GNSS} is the monitoring station coordinate estimate from broadcast ephemeris positioning, and X_{ITRF} is the station coordinate in ITRF2014.

2.2 Ephemeris Comparison Method

The broadcast ephemeris spatial datum corresponds to each navigation system's reference frame, while the precise ephemeris spatial datum is primarily maintained by IGS. Since the IGS spatial datum is consistent with ITRF2014, navigation satellite positions calculated from broadcast ephemeris can be compared with precise ephemeris to obtain transformation relationships between navigation system reference frames and ITRF. As IGS precise orbits represent satellite center-of-mass coordinates while broadcast ephemeris provides antenna phase center positions, correction from antenna phase center to center-of-mass is required.

Considering different attitude control modes for various BeiDou satellite types, satellite antenna phase center corrections are implemented as follows:

(1) IGSO/MEO Satellite Antenna Phase Center Correction Model:

$$e_z = \frac{r}{|r|}$$
$$e_y = \frac{e_z \times r_{sun}}{|e_z \times r_{sun}|}$$
$$e_x = e_y \times e_z$$

where r and r_{sun} are satellite position and Sun position vectors in the inertial frame, and e_x, e_y, e_z are transformation vectors from satellite body-fixed to Earth-fixed frame.

(2) GEO Satellite Antenna Phase Center Correction Model:

$$e_z = \frac{r}{|r|}$$
$$e_y = \frac{e_z \times v}{|e_z \times v|}$$
$$e_x = e_y \times e_z$$

where r and v are satellite position and velocity vectors in the inertial frame.

The phase center correction model is:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = R_{cis}^{cts} \times [e_x \ e_y \ e_z] \times \begin{bmatrix} x_{phs} \\ y_{phs} \\ z_{phs} \end{bmatrix}$$

where R_{cis}^{cts} is the rotation matrix from inertial to Earth-fixed frame, $x_{phs}, y_{phs}, z_{phs}$ are satellite antenna phase center offsets in the satellite body-fixed coordinate system, and X, Y, Z are satellite antenna phase center correction values.

After reducing both to the same center, differences are calculated and seven-parameter transformation is performed to obtain translation, rotation, and scale factor parameters aligning the reference frame with ITRF, using the same formula as Equation (2).

2.3 SLR Coordinate Estimation Method

The SLR coordinate estimation method is similar to the broadcast ephemeris positioning method, obtaining transformation parameters between two reference frames by comparing SLR station coordinates in the navigation system reference frame with ITRF coordinates. Laser data measures the distance from ground stations to satellite retroreflectors, featuring minimal ionospheric refraction error, high measurement precision, and immunity to clock errors. BeiDou-3 satellites provide real-time global high-precision broadcast ephemeris products based on inter-satellite link technology, with high orbit precision [8]. Moreover, all BeiDou navigation satellites are equipped with retroreflectors, enabling the use of broadcast ephemeris orbit products and high-precision SLR measurements to obtain SLR station coordinates in the BDCS frame. Comparing these with SLR station coordinates in the ITRF frame yields transformation parameters between the two reference frames [9,10].

Broadcast ephemeris-calculated orbits are corrected from phase center to center-of-mass coordinates using the same method described above, with satellite center-of-mass corrections applied. A one-month observation arc is used to estimate SLR station coordinates, which are then compared with coordinates from ITRF2014 at the current epoch, followed by seven-parameter calculation using the same formula as Equation (2).

Against the backdrop of Sino-Russian cooperation, requirements for pseudorange user compatibility and interoperability have been proposed. The SLR coordinate estimation method was used to compare the seven transformation parameters between BDCS and PZ-90.

The transformation formula between different reference frames, using BDCS and PZ-90 as an example, is derived as follows. From Equation (2), the transformation formula between PZ-90 and ITRF is:

$$X_{ITRF} = X'_{trans} + (1 + X'_{scale}) \times X'_{rot} \times X_{PZ-90}$$

Substituting this into Equation (2) yields:

$$\begin{aligned} X_{bdcs} &= X_{trans} + (1 + X_{scale}) \times X_{rot} \times (X'_{trans} + (1 + X'_{scale}) \times X'_{rot} \times X_{PZ-90}) \\ &= X''_{trans} + (1 + X''_{scale}) \times X''_{rot} \times X_{PZ-90} \end{aligned}$$

From this, the transformation parameters between BDCS and PZ-90 are obtained:

$$\begin{aligned} X''_{trans} &= (1 + X_{scale}) \times X_{rot} \times X'_{trans} + X_{trans} \\ X''_{scale} &= X_{scale} + X'_{scale} + X_{scale} \times X'_{scale} \\ X''_{rot} &= X_{rot} \times X'_{rot} \end{aligned}$$

3.1 Test Conditions

Monitoring stations selected for this study require stable reception of BeiDou-3 B1I/B3I signals with at least four BeiDou-3 satellites available per epoch. After screening, data from 15 stations were used: domestic stations wuh2, urum; overseas stations tuva, zim2, ulab, arht, met3, savo, bor1, pove, ganp, moiu, sthl, pots, sgoc. provides statistics on the number of available BeiDou-3 satellites per epoch for each station. [Figure 1: see original paper] shows the distribution of monitoring station locations.

3.2 Broadcast Ephemeris Positioning Results

Using 30-second sampling B1/B3I dual-frequency pseudorange and phase data from global monitoring stations and broadcast ephemeris from January to December 2019, daily monitoring station coordinates were calculated. Annual coordinate estimate differences from ITRF coordinates were statistically analyzed, with a set of seven parameters calculated daily.

Since BeiDou-3 and BeiDou-2 satellites differ in spatial signal accuracy, two processing strategies were compared: (1) using only BeiDou-3 satellites (C19–C37) with B1I/B3I dual-frequency combination, and (2) using a BeiDou-2/BeiDou-3 mixed constellation (C01–C37), where BeiDou-2 employed B1I/B3I and B1I/B2I dual-frequency combinations while BeiDou-3 used B1I/B3I dual-frequency combination.

Statistical results of coordinate difference sequences between BeiDou-3 processing estimates and ITRF for each station throughout 2019 are presented in . Using BeiDou-3 data from February 2019, satellite clock errors, receiver clock errors, atmospheric delays, and phase ambiguities were removed through broadcast ephemeris positioning, yielding O-C time series shown in [Figure 2: see original paper], with average residuals between -0.2 m and +0.2 m.

and [Figure 3: see original paper] present the seven transformation parameter results from the BeiDou-3 broadcast ephemeris positioning method.

For the BeiDou-2/BeiDou-3 combined processing, coordinate difference sequences with ITRF throughout 2019 are shown in . Using BeiDou-2/BeiDou-3 data from February 2019, O-C time series were obtained after error correction, as shown in [Figure 4: see original paper]. BeiDou-3 average residuals ranged between -0.5 m and +0.5 m, while BeiDou-2 average residuals ranged between -0.7 m and +0.7 m.

Since BeiDou-2 is a regional service system without overseas observation and injection stations, long-term forecast products were used for global assessment. BeiDou-3, utilizing inter-satellite link observations with ground stations combined with space-ground data for joint orbit determination, achieves higher orbit precision. Consequently, BeiDou-3 satellite spatial signal accuracy is superior to BeiDou-2, as shown in and [Figure 5: see original paper].

3.3 Ephemeris Comparison Results

Using 25 days of precise and broadcast ephemeris data from January 3 to January 27, 2019 (with precise ephemeris being post-processed products from Shanghai Astronomical Observatory), satellite coordinates in BDCS and ITRF frames were calculated by fitting broadcast ephemeris to precise ephemeris. Twenty-five days of coordinate differences were statistically analyzed, with a set of seven parameters calculated daily.

Comparing Shanghai Astronomical Observatory's post-processed BeiDou precise ephemeris with broadcast ephemeris, daily seven parameters were calculated and monthly averages computed, as shown in and [Figure 6: see original paper].

3.4 SLR Coordinate Estimation Results

Using SLR measurement data and broadcast ephemeris, SLR station coordinates were calculated for both BDS and GLONASS systems, with results shown in and . For BDS, four BeiDou-3 satellites yielded 3,330 normal points; for GLONASS, 21 operational satellites yielded 4,317 normal points.

The residual time series for 2019 solved by the SLR estimation method (see [Figure 7: see original paper]) indicates that BDS spatial signal accuracy residuals under this method fall within \$±\$0.15 m.

Using SLR measurement data and broadcast ephemeris, SLR station coordinates were estimated. Data consisted of ILRS laser ranging data for BDS throughout 2019. Due to sparse SLR data sampling, station coordinates were estimated monthly, and seven transformation parameters between BDCS and ITRF were calculated. Additionally, using GLONASS ILRS laser ranging data from January 2019, seven transformation parameters between PZ-90 and ITRF, as well as between BDCS and PZ-90, were calculated, with results shown in and [Figure 8: see original paper].

3.5 Results Analysis

This paper employs three methods—broadcast ephemeris positioning, broadcast versus precise ephemeris comparison, and SLR station coordinate estimation—to calculate BDCS implementation accuracy. The first method uses both BeiDou-2/BeiDou-3 mixed constellation and BeiDou-3-only strategies for precise coordinate estimation.

For BeiDou-3, the seven-parameter conversion yields translation parameters of 3.3 cm, -0.7 cm, and 3.9 cm; rotation parameters of -2.19 mas, 0.08 mas, and -0.43 mas; and a scale factor of 7.6×10^{-13}. For the BeiDou-2/BeiDou-3 mixed constellation, translation parameters are 7.5 cm, 7.3 cm, and 8.5 cm; rotation parameters are -2.65 mas, -2.14 mas, and 0.76 mas; and the scale factor is -2.3×10^{-10}.

The second method, comparing broadcast and precise ephemeris, yields translation parameters of -3.4 cm, 0.5 cm, and 3.5 cm; rotation parameters of 0.01 mas, 0.4 mas, and 0.04 mas; and a scale factor of -2.6×10^{-11}.

The third method uses precise ephemeris and SLR data to estimate station coordinates. For BDS, translation parameters are -4.8 cm, 3.4 cm, and 2.2 cm; rotation parameters are 2.5 mas, -2.6 mas, and 0.8 mas; and the scale factor is 4×10^{-12}. For GLONASS, translation parameters are -0.045 cm, 1.6 cm, and -1.2 cm; rotation parameters are -1.31 mas, -0.99 mas, and -0.94 mas; and the scale factor is -1.802×10^{-9}.

The transformation between BDS and GLONASS yields translation parameters of -0.3 cm, 1.7 cm, and -6.5 cm; rotation parameters of -4.51 mas, 0.01 mas, and -0.85 mas; and a scale factor of -2.786 $\times 10^{-9}$.

These results demonstrate that formal errors of the seven parameters calculated by all three methods are at the centimeter level, indicating that BDCS-ITRF alignment accuracy is at the centimeter level.

Comparing the three methods, ephemeris comparison and SLR coordinate estimation achieve higher monitoring precision than broadcast ephemeris positioning because they incorporate post-processed precise products. BeiDou satellite broadcast ephemeris contains orbit errors and PCO errors, resulting in lower precision that affects reference frame implementation accuracy monitoring. However, as broadcast ephemeris precision improves, monitoring accuracy will gradually increase.

4 Conclusion

This paper presents three methods for calculating BDCS implementation accuracy and conducts experiments using 2019 full-year data, leading to the following conclusions:

(1) Calculations using actual data from all three methods can satisfy RNSS meter-level user compatibility and interoperability requirements. The broadcast ephemeris positioning method enables real-time reference frame monitoring, though monitoring precision is determined by broadcast ephemeris accuracy. The ephemeris comparison method improves monitoring precision through post-processed products but lacks timeliness. The SLR coordinate estimation method provides the highest precision among the three methods, but currently limited laser ranging data volume restricts analysis to long-term monitoring results.

(2) The selected IGS stations in this study all require reception of BeiDou-3 B1I/B3I signals, limiting the number of stations participating in the experiment. Results from BeiDou-2/BeiDou-3 combined processing are consistent with BeiDou-3-only processing at the centimeter level. Therefore, future work can incorporate more ground monitoring stations, primarily IGS core stations, for global network solution calculations to monitor the reference frame, enhancing result reliability.

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Note: Figure translations are in progress. See original paper for figures.