remote sensing

Communication

SISRE of BDS-3 MEO: Evolution as Well as Comparison between D1 and B-CNAV (B-CNAV1, B-CNAV2) Navigation Messages

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Abstract: The signal-in-space range error (SISRE) has a direct impact on the performance of global navigation satellite systems (GNSSs). It is an important indicator of navigation satellite space server performance. The new B-CNAV navigation messages (B-CNAV1 and B-CNAV2) are broadcast on the satellites of the Beidou Global Navigation Satellite System (BDS-3), and they are different from D1 navigation messages in satellite orbit parameters. The orbit accuracy of B-CNAV navigation messages lacks analyses and comparisons with D1. The accuracy and stability of the new hydrogen and rubidium clocks on BDS-3 satellites need annual analyses of long time series, which will affect the service quality of this system. Based on precise ephemeris products from the Center for Orbit Determination in Europe (COD), the orbit error, clock error, and SISRE of 24 medium Earth orbit (MEO) satellite D1 and B-CNAV navigation messages of BDS-3 were computed, analyzed, and compared. Their annual evolution processes for the entire year of 2022 were studied. Thanks to the use of inter-satellite links (ISLs) adopted by BDS-3 MEO satellites, the ages of the ephemeris are accurate and the percent of ages of data, ephemerides (AODEs), and ages of data and clocks (AODCs) shorter than 12 h were 99.95% and 99.96%, respectively. In addition, the broadcast orbit performance was also improved by ISLs. The root mean square (RMS) values of the BDS-3 MEO broadcast ephemeris orbit error were 0.067 m, 0.273 m, and 0.297 m in the radial, cross, and along directions, respectively. Moreover, the 3D RMS value was 0.450 m. Thanks to the use of new orbit parameters in the B-CNAV navigation messages of BDS-3 MEO, its satellite orbit accuracy was obviously better than that of D1 in the radial direction. Its improved accuracy can reach up to about 1.2 cm, and the percentage of its accuracy improvement was about 19.06%. With respect to clock errors, the timescale differences between the two clock products were eliminated to assess the accuracy of broadcasting ephemeris clock errors. A standard deviation value of 0.256 m shows good performances as a result of the use of the two new types of atomic clocks, although the RMS value was 0.541 m due to a nonzero mean bias. Overall, the accuracy of atomic clocks was good. For the new hydrogen and rubidium atomic clocks, their RMS and standard deviation were 0.563 m and 0.231 m and 0.519 m and 0.281 m, respectively. The stability of the former was better than that of the latter. However, due to the nonzero mean bias the latter was better than the former in accuracy. The RMS value of the SISRE of BDS-3 MEO's broadcast ephemeris was 0.556 m, and the value was 0.920 m when it had a 95% confidence level. In contrast, after deducting the influence of the clock error, the value of SISRE_ORB was 0.092 m. Since the satellite clock error was substantially larger than the orbit radial error, the SISRE was mainly affected by the clock error, and their annual evolutions were consistent. Because of the improvement to the B-CNAV's navigation message with respect to orbit radial accuracy, SISRE_ORB has improved in accuracy. Compared to D1, it had a significant effect on improving the accuracy of SISRE_ORB, and the percentage of the accuracy improvement was 8.40%.

Keywords: BDS-3 MEO; D1 and B-CNAV navigation messages; orbit and clock errors; SISRE

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1. Introduction

The BeiDou Navigation Satellite System (BDS) is one of the four global navigation satellite systems (GNSSs). The first-generation BeiDou system (the BeiDou Navigation Satellite Experimental System, BDS-1) was first used in 2000 and offered limited coverage and navigation services mainly for users in China and neighboring regions. The second generation of the system, officially called the BeiDou Regional Navigation Satellite System (BDS-2), was operational in December 2011. Since December 2012, it has provided services to customers in the Asia-Pacific region. In 2015, the construction of the third-generation BeiDou system (BDS-3) began. On 27 December 2018, BDS-3 started to provide global services. The 35th and final BDS-3 satellite was launched into orbit on 23 June 2020.

Compared with BDS-2, BDS-3 has been upgraded from being a regional service to providing navigation and positioning services for global users, and its service performance is better [1,2]. With respect to its designed signal, BDS-3 provides navigation signals of multiple frequencies and can provide high-precision services via combined multi-frequency signals. BDS-3 is backward compatible with the B1I and B3I signals of BDS-2 and adds B1C and B2a signals. Two new navigation messages, B-CNAV1 and B-CNAV2, were modulated on the two new signals, and they adopted new orbital parameters (18 parameters) with higher orbit description accuracy [3–5]. Compared to the rubidium atomic clock of BDS-2 [6–8], BDS-3 uses a new type of rubidium atomic clock with a daily stability of 10^{-14} and a new type of hydrogen atomic clock with a daily stability of 10^{-15}, which improves the performance and service life of satellites [9–11]. In addition, BDS-3 satellites are equipped with an inter-satellite link (ISL) payload. Since monitoring stations are only deployed in China, ISLs play an important role in broadcast message generation and update [9,12,13].

A signal-in-space range error (SISRE) mainly includes satellite orbit errors and clock errors, and its accuracy has a direct impact on satellite navigation and positioning [14–16]. Changes in the accuracy of SISRE are an important factor affecting the performance of GNSS services [13,17,18]. Therefore, it is of great significance to study and analyze the orbit and clock errors of a satellite broadcast ephemeris for evaluating the basic service performance of GNSSs. Currently, there are many studies evaluating the SISRE, orbit, and clock errors of GNSSs [19–24], and some studies have arrived at significative conclusions with respect to BDS [10,14–17,21]. Montenbruck evaluated BDS-2's navigation messages [21]. Wu assessed the long-term SISRE accuracy of BDS-2 from 2013 to 2016 [25]. An average root mean square (RMS) of 1 to 2 m was computed for SISRE [14,15]. For BDS-3, the SISRE accuracy shows a noticeable improvement compared to BDS-2 [1,2]. Guo assessed the technical characteristics and service performance of BDS-3, and Lv carried out an initial assessment of BDS-3 SISRE [10,17]. They arrived at similar conclusions: the 3D RMS of the broadcast orbit error was less than 0.6 m, and the RMS of the clock error was about 0.5 m. Since the time span of the data used was less than 2 months, there is a lack of analysis with respect to the long-term annual evolution of BDS-3 SISRE. Furthermore, the accuracy analysis of B-CNAV navigation messages has not attracted sufficient attention, and the accuracy of hydrogen and rubidium atomic clocks should be counted separately to grasp the service performance of new atomic clocks.

In this paper, the orbit, clock error, and the SISRE evolution of the 24 medium Earth orbit (MEO) satellites of BDS-3 were analyzed and compared using data for the entire year of 2022. In order to evaluate the accuracy of the D1 and B-CNAV navigation messages of the 24 MEO satellites of BDS-3, this article used the precision products of the Center for Orbit Determination in Europe (COD) as reference values.

2. Methodology

2.1. Reference Frame and Time Difference

The BeiDou coordinate system (BDCS) was adopted by the BDS-3 broadcast ephemeris, while the precise orbit of IGS is referred to as the international terrestrial reference frame (ITRF) [1,5,26–28]. The difference between BDCS and ITRF is about 4.0 cm [10]. The impact of this deviation is not considered in this paper, because it is negligible with regard to the orbit accuracy of navigation. The BDS-3 broadcast ephemeris time was based on BeiDou time (BDT), and the precise ephemeris of IGS was based on GPS time (GPST) [1,5,29–31]. In order to assess the clock error accuracy of the BDS-3 broadcast ephemeris, the time was unified as GPST.

2.2. Antenna Offset Correction

The precise ephemeris product of IGS provides the center-of-mass (CoM) coordinate of the respective space vehicle, but the position reference point of BDS-3 broadcast ephemeris is the antenna phase center (APC) of a single-frequency B3I signal [3–5,32,33]. With respect to the orbit error, this inconsistency causes meter-level differences in the direction of the antenna in the spacecraft frame [14]. In order to assess the position accuracy of the BDS-3 broadcast ephemeris, antenna offset vectors (http://www.csno-tarc.cn/datacenter/satelliteparameters, accessed on 1 January 2023) provided by the satellite manufacturer correct the position reference point of the broadcast ephemeris from APC to CoM. The correction in detail from APC to COM can be found in reference [14].

2.3. Clock Correction

The clock offset values of precise and broadcast ephemerides cannot be compared directly. The time group delay of B3I was regarded as the reference time group delay (TGD), which was included in the broadcast clock correction parameter of BDS-3 [3–5,32,33]. However, the ionospheric-free combination of B1I and B3I was regarded as the reference time group delay, which was included in COD's precise clock correction parameter [8,10,16]. When working with other signal combinations, TGD must be employed [14,34–36]. There are differences in the underlying realization of the GNSS-specific system's time scales. These differences are typically larger than the inherent precision of clock solutions, affect all satellites of a constellation in the same manner, and result in a systematic bias that may vary from epoch to epoch. To account for this bias, an ensemble clock difference was therefore computed at each epoch from the average broadcast-minus-precise clock values of satellites in a constellation. Subsequently, each clock offset difference was corrected for this ensemble's average [14,16,17]. Therefore, the formula for evaluating the accuracy of clock offsets is represented as

$$\begin{cases} \Delta t^i = \mathrm{d}t^i - \mu \\ \mathrm{d}t^i = t^i_{sp3} - t^i_{brd(1,3)} \\ t^i_{brd(1,3)} = t^i_{brd} - \frac{f_1^2 \mathrm{TGD}_1}{f_1^2 - f_3^2} \end{cases} \quad (1)$$

where Δt^i is the accuracy of clock offset of the i satellite; $\mathrm{d}t^i$ is the one time difference between the precise ephemeris clock offset t^i_{sp3} and the broadcast ephemeris clock offset $t^i_{brd(1,3)}$, which is corrected via the group delay correction of TGD_1; t^i_{brd} is the satellite clock offset obtained from direct computation; f_1 represents the value of B1I's frequency; f_3 represents the value of B3I's frequency; and $\mu = \sum_{i=1}^{n} \mathrm{d}t^i$ is the average value of $\mathrm{d}t^i$, while i is from 1 to n (n is the number of the satellites).

2.4. SISRE Model

SISRE is a comprehensive index for evaluating the accuracy of broadcast ephemerides, and it reflects the comprehensive influence of the difference between the broadcast ephemeris and the true value of the position and clock offset in the line-of-slight direction [10,15,16,18]. The 24 MEO satellites of BDS-3, SISRE and SISRE_ORB, which do not consider the influence of clock errors, can be represented as

$$\begin{cases} \mathrm{SISRE} = \sqrt{(w_1 R - T)^2 + w_2^2(A^2 + C^2)} \\ \mathrm{SISRE\_ORB} = \sqrt{w_1^2 R^2 + w_2^2(A^2 + C^2)} \end{cases} \quad (2)$$

where R, A, and C are orbit errors in radial, along, and cross directions, while T represents clock errors converted to distance. w_1 and w_2 are weight factors for the SISRE and SISRE_ORB, and they are related to a specific constellation. According to Montenbruck, Lv, and Chen, the values for w_1 and w_2 were 0.982 and 0.132, respectively, with a satellite cutoff elevation of 5° in this paper [13,15,17].

3. Results

3.1. Broadcast Ephemerides

Different from the D1 navigation message with 16 orbit parameters, the number of orbit parameters of the B-CNAV (B-CNAV1 and B-CNAV2) for BDS-3 MEO satellites was 18. B-CNAV1 and B-CNAV2 have the same orbit parameters as B-CNAV. The difference between the two navigation messages is reflected in the Kepler orbit parameters' semi-major axis (A) and the mean motion (n). The square root of the semi-major axis ($\sqrt{A}$) is used to describe A in the D1 navigation message, but the semi-major axis difference at the reference time (ΔA) and the change rate in the semi-major axis ($\dot{A}$) are used in B-CNAV navigation messages. Similarly, the mean motion difference from the computed value (Δn) is used to describe n in D1 navigation, but the mean motion difference from the computed value at reference time (Δn_0) and the rate of the mean motion difference from the computed value at reference time ($\Delta \dot{n}_0$) are used in the B-CNAV navigation message. The new orbit parameters describe the change in satellite orbit in more detail [3–5,32,33]. The broadcast ephemeris produced by IGS and the broadcast ephemeris produced by the Test and Assessment Research Center of China Satellite Navigation Office (TARC) were used to study the evolution of SISRE and the comparison between B-CNAV and D1 navigation messages.

The IGS product only contains 16-parameter orbit information. The TARC product contains the 18-parameter orbit information of B-CNAV. The broadcast ephemeris of BDS was one epoch per hour to record orbit and clock offset information [6,7,21,35]. In this study, in order to analyze the difference between two types of navigation messages (D1 and B-CNAV), we compared them at the same epochs using the ephemeris products from the Center for Orbit Determination in Europe (COD) as the reference values. Figure 1 shows the integrity of the ephemeris products. It can be observed that the ephemeris product of IGS and COD was complete, and the ephemeris product of TARC was partially missing in 2022. For TARC, the ephemeris product was missing with respect to six days (the DOY was 134, 135, 274, 275, 288, 289) of data.

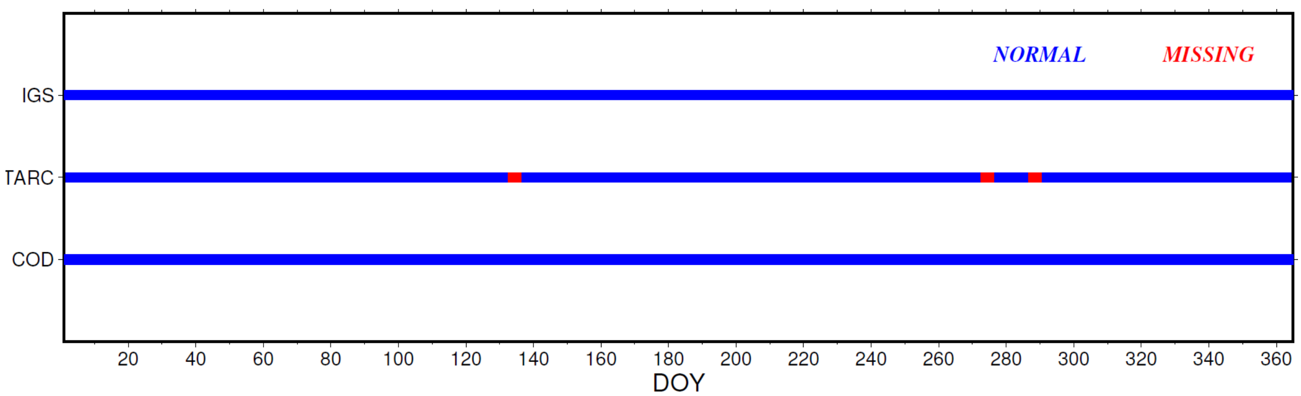

Figure 1. Missing broadcast ephemeris of the international GNSS service (IGS), the Test and Assessment Research Center of China Satellite Navigation Office (TARC), and the missing BDS ephemeris products obtained from the Center for Orbit Determination in Europe (COD) from DOY 001 to 365, 2022.

3.2. Selection of Navigation Data Records

The accuracy of the broadcast ephemeris is directly affected by the ephemeris's age [14,15,37]. The BDS-3 broadcast ephemeris is generated using ISL observations, and this overcomes the non-global uniform distribution shortcoming of its ground observation sites. The cross-links of the constellation are used to update the navigation message [10,12]. The ephemeris age of BDS-3 has been greatly improved compared to that of BDS-2 [17]. In this study, the proportions of orbit age and clock offset age from the D1 navigation messages of BDS-3 MEO satellites shorter than 12 h were 99.95% and 99.96%, respectively. The corresponding proportions from the B-CNAV navigation messages were both 90.17%. The statistical results showed that the ages of the two navigation messages were healthy and suitable for analyses.

3.3. Orbit Error

The precision ephemeris products of COD were used as true values to evaluate the accuracy of the D1 and B-CNAV navigation messages of the 24 MEO satellites of BDS-3. According to a one epoch per hour BDS-3 broadcast ephemeris, the orbit position errors of the 16-parameter broadcast ephemeris of 2022 are plotted as a time series in Figure 2. The figure shows the annual evolution of the orbit position's accuracy in the radial, cross, and along directions. The D1 navigation message of the BDS-3 MEO constellation exhibits mean orbit errors of −0.032 +/− 0.057 m, −0.001 +/− 0.273 m, and 0.037 +/− 0.293 m in the three directions, respectively, where the preceding values represent the mean value, and the specified uncertainties reflect the standard deviation. For the entire MEO satellite constellation, the mean values of the orbit errors were very small. This also shows that the antenna offset correction used was effective and reasonable. Overall, for the entire year of 2022, the orbit position accuracy of BDS-3 MEO's broadcast ephemeris was the highest and the most stable in the radial direction and was slightly worse and fluctuating in the cross and along directions. For the C19 satellite, there was a significant change in orbit accuracy in 2022, especially in the radial direction.

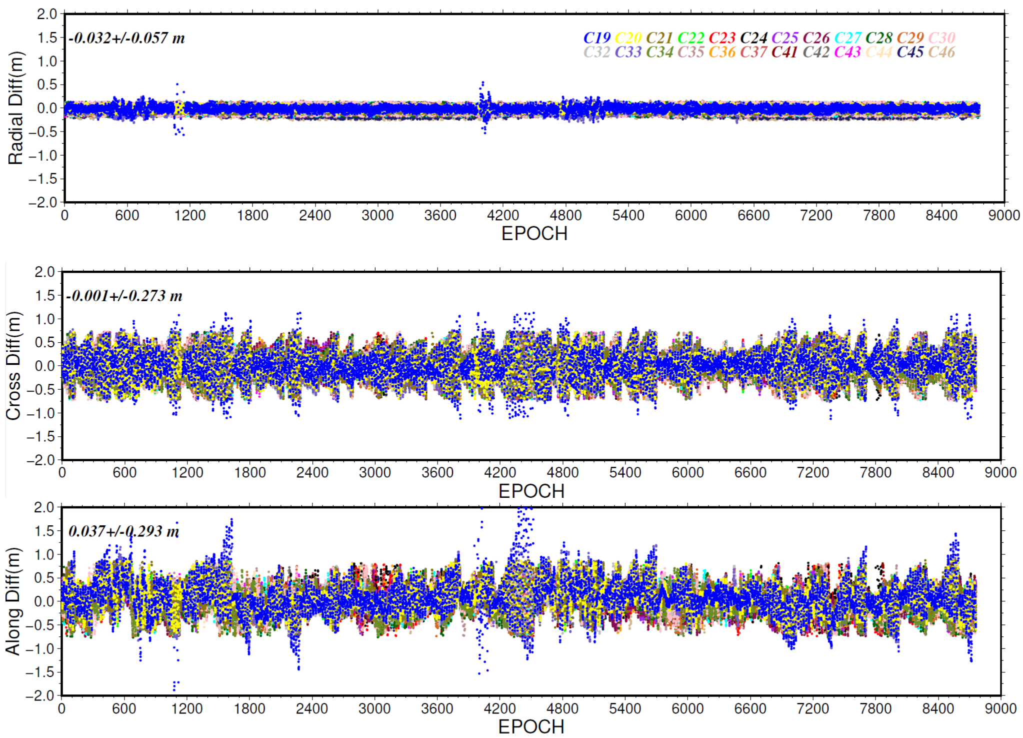

Figure 2. BDS-3 orbit differences (EPOCH 1-8760, 2022) between D1 navigation message and precise products. Each satellite has its own color.

The annual RMS statistics of the orbit errors from the D1 navigation message are listed in Table 1, and the accuracies of the orbit errors in 3D, along, cross, and radial directions are listed. Generally, the radial accuracy was the best, and cross accuracy was better than that of the along direction. In order to clearly analyze the orbit position's accuracy, the annual RMS accuracy statistic of every satellite was calculated and is shown in Figure 3. It can be observed that the orbit position accuracies of the 24 MEO satellites have similar variations in the three directions and in 3D.

Table 1. The RMS statistic of the BDS-3 MEO orbit errors of the D1 navigation message (unit: m).

TYPE	Along	Cross	Radial	3D
BDS-3 MEO	0.297	0.273	0.067	0.450

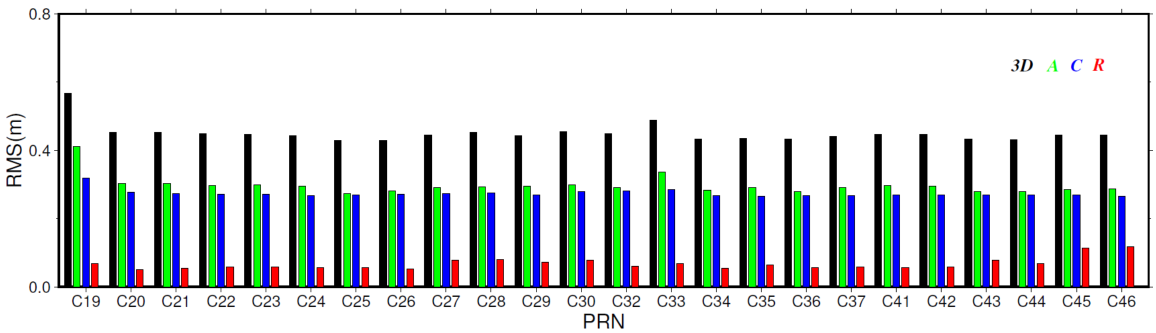

Figure 3. The RMS statistic of every satellite orbit error of the D1 navigation message (unit: m): 3D RMS (black), along RMS (green), cross RMS (blue), and radial RMS (red).

Table 2 shows the RMS statistic and comparison of the orbit error between the D1 and B-CNAV navigation messages. Moreover, the accuracy improvement ratio of B-CNAV messages compared to D1's is shown. It can be observed in Table 2 that compared with the D1 navigation message, the orbit position accuracy of the B-CNAV message had no difference in the cross and along directions but had significant improvements in the radial direction, and its accuracy improvement ratio was 19.06%. This also improved the orbit accuracy in 3D directions. The accuracy improvement ratio of the 24 satellites of the B-CNAV navigation message is plotted in Figure 4. For each satellite, the orbit accuracy was hardly improved in the along and cross directions, but it was improved to varying degrees in the radial direction.

Table 2. The RMS statistic and comparison of orbit errors between two types of navigation messages (unit: m).

TYPE	Along	Cross	Radial	3D
Diff	0.000	0.000	0.012	0.002
Imp	0.00%	0.00%	19.06%	0.46%

3.4. Clock Error

The clock offset information in the D1 and B-CNAV navigation messages of BDS-3 MEO was the same. Since the D1 navigation message had more epochs and was more complete, we used it to evaluate the accuracy of the clock error. According to one epoch per hour of the BDS-3 MEO broadcast ephemeris, the clock offset differences of each satellite between the broadcast ephemeris and precision ephemeris were calculated and are shown in Figure 5. The figure shows the annual clock error evolution process of every satellite. The mean value and standard deviation of the clock error of the entire MEO constellation were 0.004 m and 0.256 m, respectively. In terms of the mean value, the systematic deviation caused by different reference clocks was eliminated for the constellation.

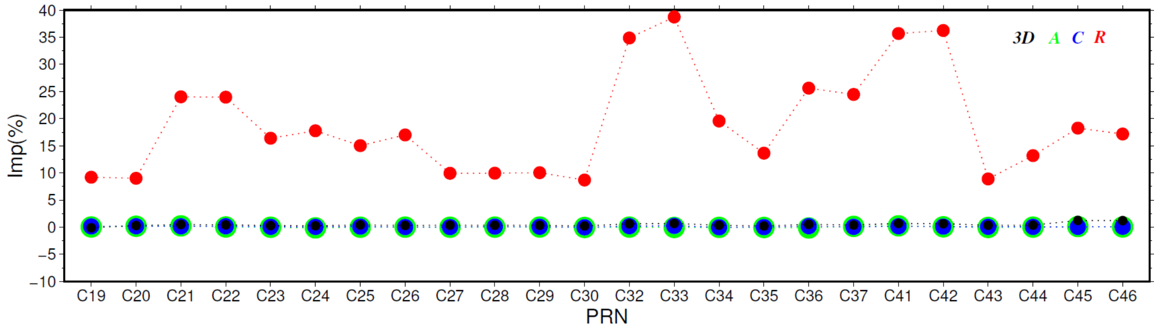

Figure 4. The orbit improvement ratio of each satellite of B-CNAV navigation messages: 3D improvement ratio (black), along improvement ratio (green), cross improvement ratio (blue), and radial improvement ratio (red).

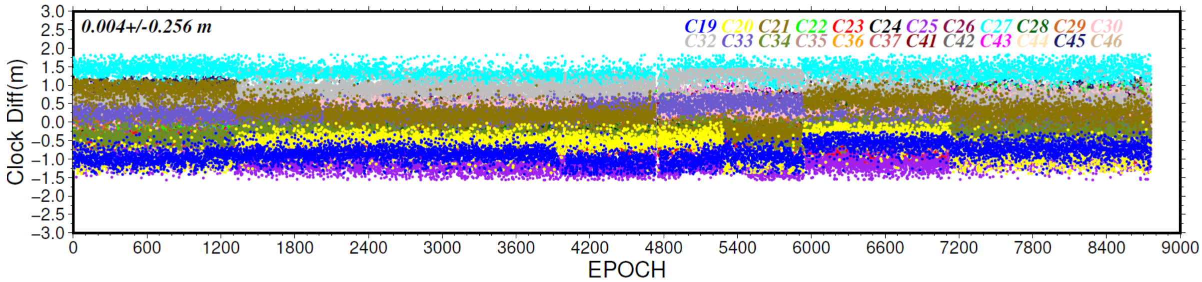

Figure 5. BDS-3 clock offset differences (EPOCH 1-8760, 2022) between the broadcast ephemeris and precise product. Each satellite has its own color.

As new hydrogen (C25 C26 C27 C28 C29 C30 C34 C35 C41 C42 C43 C44) and rubidium atomic clocks (C19 C20 C21 C22 C23 C24 C32 C33 C36 C37 C45 C46) are carried on BDS-3 MEO satellites, we distinguish them when analyzing clock error accuracies. Table 3 shows a statistical analysis of the mean value, standard deviation, and RMS of the annual clock error of the BDS-3 MEO broadcast ephemeris. At the same time, Figure 6 gives the annual accuracy statistic of hydrogen and rubidium atomic clocks for each satellite. It can be observed in Table 3 that the accuracy of the BDS-3 MEO broadcast ephemeris clock error was 0.541 m. The standard deviations of two new types of atomic clocks showed that the stability of the hydrogen atomic clock was better than that of the rubidium atomic clock. For a single satellite, the average clock error was not zero, which resulted in a systematic deviation. Due to the existence of systematic deviations, the clock error accuracy of the hydrogen atomic clock was 0.563 m, and it was lower than the accuracy of the rubidium atomic clock, which was 0.519 m. Figure 6 shows that the satellite of C29 had the best accuracy and stability with respect to the hydrogen atomic clock, while C37 had the smallest systematic deviation and the best accuracy with respect to the rubidium atomic clock. For a single satellite, the accuracy of the satellite clock error was greatly affected by the obvious systematic deviation. The systematic deviation was related to the delay deviation of the equipment, and it can be eliminated by adjusting the TGD parameter of the navigation message [10].

Table 3. The accuracy statistic of BDS-3 broadcast ephemeris clock errors (unit: m).

TYPE	Mean	STD	RMS
H	0.003	0.231	0.563
Rb	0.005	0.281	0.519
ALL	0.004	0.256	0.541

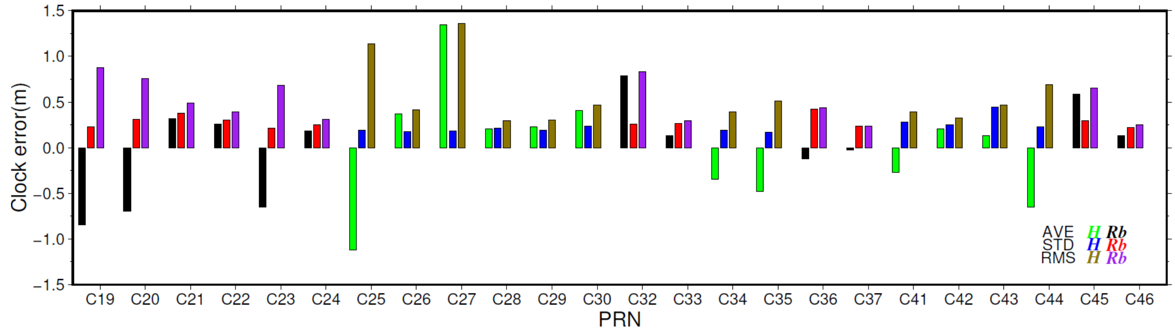

Figure 6. BDS-3 clock error accuracy statistic of each satellite (unit: m). Mean value of the hydrogen atomic clock (green), mean value of the rubidium atomic clock (black), standard value of the hydrogen atomic clock (blue), standard value of the rubidium atomic clock (red), RMS value of the hydrogen atomic clock (brown), and RMS value of the rubidium atomic clock (purple).

3.5. SISRE

Figure 7 shows the annual evolution of the daily SISRE and SISRE_ORB of BDS-3 D1 navigation messages in 2022. SISRE_ORB was generated by SISRE via deducting the influence of the clock error. The mean value and standard deviation of SISRE_ORB were 0.083 m and 0.040 m, respectively, and the 24 MEO satellites of BDS-3 had similar and stable daily variation trends. The mean value and standard deviation of SISRE were 0.508 m and 0.210 m, respectively. Via the comparison between SISRE and SISRE_ORB, it was obvious that the satellites presented different trends and fluctuations due to the strong influence of the clock error. For SISRE_ORB, which was mainly affected by the orbit radial error, there was a significant change in C19, and this was consistent with the performance of orbit accuracies in the radial direction.

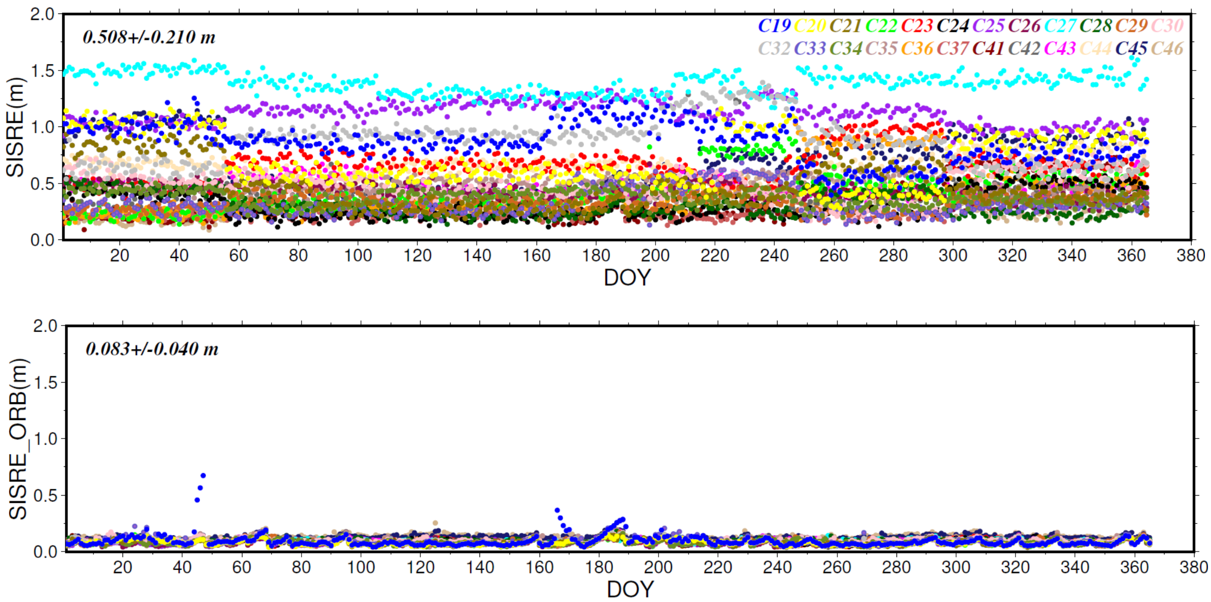

Figure 7. The daily accuracy (DOY 1-365, 2022) of SISRE and SISRE_ORB of the BDS-3 D1 navigation message (unit: m). Each satellite has its own color.

The RMS statistics of SISRE_ORB, SISRE, and 95%SISRE, which denote the 95% confidence level of SISRE, are listed in Table 4. Their 2022 values were 0.092 m, 0.556 m, and 0.920 m, respectively. At the same time, the RMS statistics of the 24 MEO satellites of BDS-3 are plotted in Figure 8. For each satellite, the accuracy variation of SISRE_ORB was consistent with that of the orbit in the radial direction, and the accuracy variations of SISRE and 95%SISRE were consistent with that of the clock error. This was because SISRE was mainly affected by the orbit radial error and clock error, and the accuracy of the former was one order of magnitude better than that of the latter. After deducting the influence of the clock error, the accuracy of SISRE was high and stable. Moreover, the annual evolution of SISRE was dominated by the satellite clock error. The satellites of C29 and C37 had the best accuracy of SISRE, and this was consistent with the accuracy results of the clock error.

Table 4. The RMS statistics of SISRE_ORB, SISRE, and 95%SISRE of the D1 navigation message (units: m).

TYPE	SISRE_ORB	SISRE	95%SISRE
BDS-3 MEO	0.092	0.556	0.920

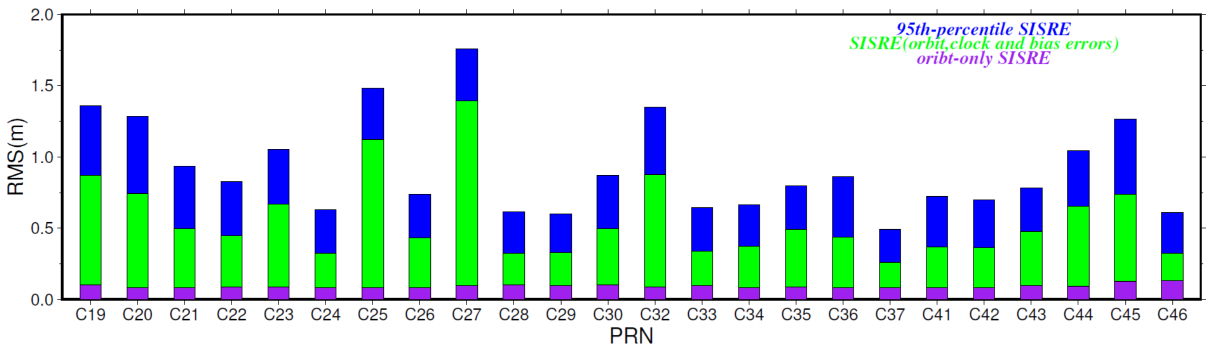

Figure 8. The RMS statistics of SISRE_ORB, SISRE, and 95%SISRE of the D1 navigation message, for every satellite (unit: m): 95% SISRE RMS (blue), SISRE (orbit, clock, and bias errors), RMS (green), and orbit-only SISRE RMS (purple).

The annual RMS statistics results of the SISRE_ORB and SISRE of D1 and B-CNAV navigation messages as well as their comparison are listed in Table 5. The accuracy of SISRE_ORB from B-CNAV navigation messages was better than that of the D1. Due to the improvement in the orbit radical direction, the improvement ratio of SISRE_ORB reached 8.40%. Because SISRE was mainly affected by the satellite clock error, its improvement ratio was small. The improvement ratios of each satellite are plotted in Figure 9. For each satellite, the improvement ratio of SISRE_ORB was positive, and the improvement ratio of SISRE exhibited both positive and negative values. In this case, SISRE_ORB was mainly affected by the orbit radial error, while SISRE was affected by the dual effects of the orbit radial error and clock error.

Table 5. The RMS statistics and comparison of SISRE_ORB and SISRE (unit: m).

TYPE	SISRE_ORB	SISRE
Diff	0.008	0.003
Imp	8.40%	0.56%

The reference standards for the SISRE of D1 and B-CNAV navigation messages were not more than 1.0 m and 0.6 m, respectively [2]. For D1, the analyzed SISRE was 0.556 m, which was better than the reference value (1.0 m). For B-CNAV, the analyzed SISRE was 0.508 m, which was better than the reference value (0.6 m). It was obvious that the SISRE of BDS-3 MEO was better than its reference standard.

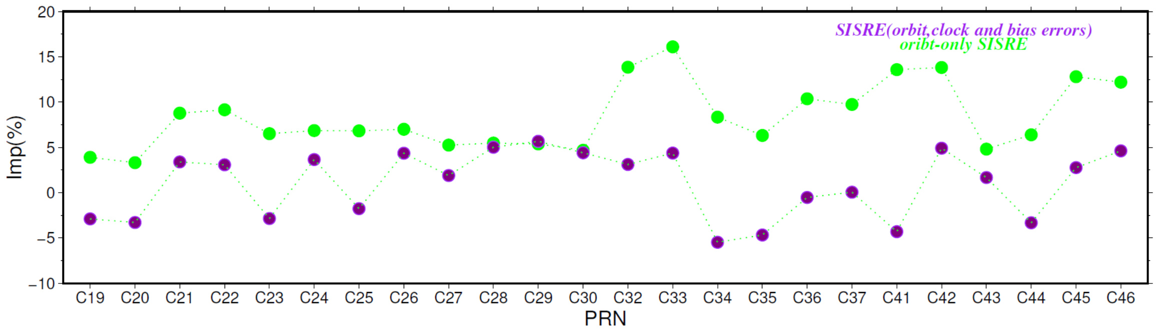

Figure 9. The improvement ratios of SISRE_ORB of each satellite of the B-CNAV navigation message. SISRE (orbit, clock, and bias errors) improvement ratio (purple) and orbit-only SISRE improvement ratio (green).

4. Conclusions

Based on the precise ephemeris products provided by COD, we studied the annual evolution of the orbit error, clock error, and SISRE of 24 MEO satellites of BDS-3 in 2022. At the same time, the orbit accuracy of D1 and B-CNAV navigation messages and the clock accuracy of the two new atomic clocks of BDS-3 MEO were compared and analyzed. Within this work, the performance quality of the BDS-3 MEO satellite space server was assessed, the difference between the D1 and B-CNAV navigation messages was obtained, and the annual evolutions of the accuracy of the orbit and the new atomic clocks was presented. It can be concluded that (1) the SISRE is mainly affected by the clock error, and it exhibits different evolution trends for different satellites, which is consistent with the evolution trends of clock errors. The annual RMS of SISRE was 0.556 m, and the annual RMS of 95%SISRE was 0.920 m. The SISRE_ORB of BDS-3 MEO is mainly affected by the orbit radial accuracy; it shows an evolution trend with high precision and high stability throughout the year, and its annual accuracy was 0.092 m. (2) For the orbit of the BDS-3 MEO broadcast ephemeris, its annual accuracy was the highest and most stable in the radial direction, and it had a certain degree of volatility in the cross and along directions. The orbit accuracies with respect to the three directions were 0.067 m, 0.273 m, and 0.297 m, respectively. Compared with the cross and along directions, the accuracy of the satellite orbit in the radial direction was an order of magnitude higher, and the 3D accuracy of the orbit was 0.450 m. The B-CNAV navigation message of BDS-3 MEO had obvious advantages with respect to orbit radial accuracy over D1, and its accuracy improvement ratio can reach 19.06%. This also produced obvious improvements with respect to the accuracy of SISRE_ORB, and its improvement ratio was 8.40%. (3) The annual clock error of the BDS-3 broadcast ephemeris had good performance, and its RMS was 0.541 m. For the new two types of atomic clocks, the RMS and standard deviation of hydrogen clocks were 0.563 m and 0.231 m, and the values of the rubidium clock were 0.519 m and 0.281 m, respectively. Obviously, the hydrogen clock is more stable than the rubidium clock. Due to the systematic error term in satellite clock errors, the accuracy of the hydrogen clock was lower than that of the rubidium clock.

Overall, the SISRE of BDS-3 MEO is better than the reference standards. Compared with the D1 navigation message, B-CNAV has obvious advantages in the radial accuracy of the satellite orbit. The two new types of atomic clocks have good accuracy, and the systematic deviations in satellite clock errors need to be further studied and eliminated.

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