Precision and Characteristics Analysis of Precise Satellite Clock Bias Data of BDS

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Abstract: High-precision satellite clock bias (SCB) data is a critical product for satellite navigation systems to realize accurate navigation, positioning and timing. Unlike other satellite navigation systems, the precise SCB data for the BeiDou Navigation Satellite System (BDS) are mainly determined by two methods, the Two-Way Time Transfer (TWTT) method and the Orbit Determination and Time Synchronization (ODTS) method. Awareness of the data variations obtained from different methods can be used to improve clock modeling performance, and be beneficial to higher-rate GNSS positioning and for predictions in real-time applications. We describe a comprehensive method to analyze the systematic and random characteristics of BDS SCB data obtained from TWTT and ODTS and discuss possible causes of observed variations. Some new conclusions are drawn: the data continuity of TWTT is highly related to satellite orbit types; affected by orbit error and other factors, the fitting residuals (RMS) of ODTS is 0.2 ns worse than that of TWTT on average, while the fitting precision of TWTT is 0.49 ns. There are up to 8ns periodic fluctuations in the mutual agreement between TWTT and ODTS data. The stability result shows a remarkable effect of flicker phase modulation (FLPM) noise can be seen in the period of 300-1000 s in TWTT data. All the BDS satellites display more complex, non-power law behavior due to the effects of periodic clock variations.

1. Introduction

BDS has provided regional navigation services since 2012 (CSNO 2013), and the space segment currently comprises 15 usable satellites: 5 geostationary (GEO), 7 inclined geosynchronous (IGSO) and 3 medium earth orbit (MEO). As BDS is entering a whole new stage of construction, it will provide global services in 2020 (Yang 2010; Tan et al 2016). Due to the fact that onboard atomic clocks not only serve as the on-board atomic frequency standards (AFSs) to maintain the time reference (Tan 2006; Guo 2006), but also influence the transmitted radio signals and thus directly impact the user positioning and timing accuracy since the global navigation satellite system (GNSS) is based on time measurement (Hein 2007), the uncertainty of BDS SCB will directly limit the urgent need for real-time high-performance navigation and positioning. Analyzing the SCB data is an effective and feasible way to have a thorough understanding of the working-status of on-board satellite clocks. An in-depth understanding of its characteristics is crucial to improve clock prediction strategy, refine time-frequency transfer model, and thus enhance the performance of positioning, navigation and timing (PNT). Specifically, the awareness of the systematic and random characteristics in SCB data can be used in precise clock modeling to yield high-precision prediction, which will be beneficial to real-time applications.
Some early analysis routinely demonstrated by the use of IGS satellite orbits and clocks for precise point positioning (PPP) (Zumberge et al. 1997) and the internal consistency of these products can reach the sub-cm level (Kouba and Springer 2001). Using PPP is an advisable solution to evaluate the SCB data precision, but it can’t provide other information of the clock, such as periodic signatures and frequency stability. Senior K et al. (2008) carried out an overall analysis of GPS satellite clocks, discussing inter-center mutual agreement and clock stability. It also detected four harmonic frequencies in all GPS satellite clock types and unveiled a relationship between the periodic signals and the orbital dynamics. Zhou (2015) evaluated SCB data of the BDS and provided the periodic variations in clock offset of all BDS satellites.

There are several previous investigations on GNSS satellite clocks, mainly focused on the data precision and frequency stability of the GPS satellite clocks (Senior et al. 2008; Huang 2008; Guo 2009; Wang 2014; Wang et al. 2018), Galileo satellite clocks (Steigenberger et al. 2015) and BDS satellite clocks (Steigenberger et al. 2013; Guo et al. 2017). Distinct from other GNSS, BDS adopts TWTT and ODTS methods to determine clock bias data. TWTT can eliminate ionospheric delay, satellite orbit error and many other errors, it can reach the precision of 0.34ns (Liu 2009). However, these data are generally not available to public users. In addition, ODTS solves the clock and orbit together, which is a widely used method for determining SCB, and there are more relevant algorithms and studies. Currently, three analysis centers (ACs), Center for Orbit Determination in Europe (CODE), Deutsches GeoForschungsZentrum (GFZ), and Wuhan University (WHU), use ODTS method to provide precise SCB data of the BDS. The precision of ODTS is 33ps (Senior K et al 2008), but the precision of BDS clock using ODTS can be 2ns (Wang et al 2016). Wang (2018) used TWTT results as a reference to compare with the counterpart of GEO/IGSO of WHU, but fail to provide the comparative results of CODE and GFZ products. So far, there are many studies focus on the characteristics of ODTS data of BDS SCB, but the analysis of characteristics of TWTT data and a thorough comparison between TWTT and ODTS is relatively rare. Similar to recent research into GNSS satellite clocks, the systematic and random characteristics of both TWTT and ODTS data of BDS satellite clocks are analyzed here and possible causes of observed variations are discussed.

After an overview of the algorithm of both TWTT and ODTS, the data continuity of different data sources is compared, the precision of BDS satellite clock is assessed. Next, the mutual agreement between TWTT and ODTS data is given. Because TWTT is theoretically less affected by orbit error and the clock parameter in broadcast ephemeris is computed based on this method, we use the TWTT result as a reference. Moreover, the time-domain stability variations are presented. Finally, the periodic terms on BDS satellite system are analyzed.

2. Algorithm principle
The SCB data of BDS are mainly obtained by the TWTT and ODTS methods. In this section, first, the principles of the two methods are briefly expounded. Second, the characteristics and differences between the two methods are compared and analyzed at the theoretical level. Finally, the SCB data quality evaluation and analysis scheme are given.

2.1. Principle of calculating SCB using TWTT
The TWTT method adopts a pattern of both ground station and satellite sending to and receiving from each other at the same epoch. The basic principles of this method can be summarized as follows: ground station $A$ sends ranging signal to a satellite at the time $T_0^A$ in the ground time system; that signal is received by the satellite at time $T_s$ in the satellite's clock, and observation data are sent to the ground station. At the same time, the satellite sends the ranging signal to the ground station at time $T_0^S$, and the signal is received by the ground station at time $T_d$ in the ground time system. At this point, the pseudorange measured by onboard receivers and ground receivers is (Gao 2014):
where $C$ represents the speed of light; $\Delta T_{SA}$, which is what we need, is the clock bias between the satellite clock and the ground clock; $\rho_S$ is the uplink pseudorange measurement; $\rho_S$ is the distance between the ground station and the satellite at time $T_S$; $\rho_A$ is the downlink pseudorange measurement; and $\rho_A$ is the distance between the ground station and the satellite at time $T_A$. We can obtain $\Delta T_{SA}$ when the two equations above are subtracted from each other:

$$
\Delta T_{SA} = \frac{1}{2C} \left( \rho_A - \rho_S \right) + \frac{1}{2C} \left( \rho_S - \rho_A \right)
$$

For the BDS, the ground clock time is basically BDT, so the difference between the on-board clock and the ground clock is the satellite clock bias.

2.2. Principle of calculating SCB using ODTS

ODTS is a type of method that uses GNSS observations to calculate both satellite orbit and clock bias. The ionosphere-free combination has been widely used in the process, and the quantity of the carrier phase and the pseudorange observation error equation can be expressed as follows:

$$
\nu_{k,\phi}^j (i) = \Delta t_k(i) - \Delta t'(i) + \rho_k'(i)/C + \delta \rho_{k,\text{prop}}^j (i)/C + \lambda N_k(i)/C + \varepsilon_{k,\phi}^j (i) - \lambda \Phi_k'^j (i)/C
$$

$$
\nu_{k,p}^j (i) = \Delta t_k(i) - \Delta t'(i) + \rho_k'(i)/C + \delta \rho_{k,\text{prop}}^j (i)/C + \varepsilon_{k,p}^j (i) - P_k'(i)/C
$$

where $j$ represents the satellite PRN; $k$ represents the number of ground stations; $i$ is the corresponding observation epoch; $\Delta t_k(i)$ is the user clock error; $\delta \rho_{k,\text{prop}}^j$ is the troposphere delay; $\Delta t'(i)$ means SCB; $\varepsilon_{k,\phi}^j (i)$ and $\varepsilon_{k,p}^j (i)$ are the multi-path error and non-modeled error such as observation noise; $P_k'(i)$ and $\Phi_k'^j (i)$ stand for the corresponding combination observations of the satellite and ground station at the same epoch; $\lambda$ stands for the corresponding wavelength; $\nu_{k,\phi}^j$ and $\nu_{k,p}^j$ stand for the corresponding observational error; and $\rho_k^j$ means the geometric distance between the satellite and the ground receiver at the epoch of signal emission (Li 2010).

It should be noted that during GNSS observation, there is a relative time delay between stations and satellites. When SCB parameters are solved based on the above two formulas, the normal equation is singular, so a reference clock must be introduced. On this basis, the relative clock bias between other receivers and satellites is determined. Finally, the absolute SCB can be obtained by adding the relative clock bias to the reference clock bias. There are two main ways to solve the above two equations. (1) First, the satellite clock is eliminated by using the double-differenced data to calculate the satellite orbit and other parameters, and then the fixed orbit is used to estimate the SCB by using the undifferenced mode. (2) The orbit and SCB are estimated together using the undifferenced data processing mode. These two methods have their own characteristics and can achieve excellent parameter estimation results when used properly (Li 2010; Zhao et al 2013; He et al 2013).

2.3. Characteristics of TWTT and ODTS

SCB provided by TWTT and ODTS technologies are important data sources for analyzing GNSS satellite clocks. Different from other satellite navigation systems, the BDS mainly uses the TWTT method to synchronize satellite system time with ground system time (Wang 2016).
For the TWTT method, the SCB data can be obtained by processing uplink and downlink pseudorange measurements at the same epoch. This mechanism can effectively eliminate some common errors, such as tropospheric delay, satellite orbit error and ground station coordinate error, to ensure good consistency of SCB data. Equation (2) shows all the factors that affect the accuracy of TWTT, such as the ranging accuracy of the uplink and downlink pseudorange and the difference in distance between the satellite and the ground station caused by bad time synchronization. Theoretically, the influence of pseudorange observation noise is within 0.4 ns (Liu 2009), and the errors caused by time difference can be well controlled within a small range. In short, the precision of SCB data obtained based on this method can reach the 0.1 ns level. However, the method also has obvious technical complexity, such as the precise measurement of the hardware transmission delays of the stations and satellites. Thankfully, these delays can be measured accurately (Liu 2015; Gong 2019).

For the ODTS method, regardless of whether the algorithm uses the undifferenced data to calculate satellite orbit and clock or both double-differenced and undifferenced data to estimate its orbit and clock simultaneously (Liu 2014), the precise orbit determination (POD) strategy will introduce some satellite orbit error (mostly radial component) in clock estimation. In result, the SCB data would be influenced by an orbital geometric configuration (Xu et al 2012a; Steigenberger et al 2013; Wang 2016). In addition, ODTS SCB data are obtained by solving a 3-day orbit arc. The ODTS clock is influenced by changes in the reference time of each fixed orbit arc and may have the phenomenon of day-boundary discontinuities (Defraigne 2007; Guyennon 2009; Zhou 2015b). At present, different calculation strategies may lead to slightly different results based on this method. However, carrier phase data or carrier smoothed pseudorange data are used in ODTS solutions, and the internal precision of the orbital-clock coupling error is within 0.1 ns (Senior 2008).

Based on the fact of the different characteristics, a comparative analysis of TWTT and ODTS satellite clocks are useful to identify the estimation error of BDS satellite orbit and satellite clock, and also useful to improve the estimation accuracy of them.

2.4. Quality evaluation scheme
To quantitatively analyze the BDS precise SCB data quality obtained by the two technical methods discussed above and compare the precision of SCB data quality, we design a quality evaluation process, as shown in Figure 1.
Figure 1: Data processing procedure can be divided into five parts: data continuity, data precision, spectrum analysis, mutual agreement analysis and time-domain stability analysis. The daily residuals between preprocessed data and quadratic polynomial fitting are obtained and are counted as the data precision.

In data preprocessing, since the time tag of SCB data of the ACs is based on GPST and the TWTT data is based on BDT, a time difference exists. It is necessary to unify the time tag before data quality comparison analysis. In this paper, the time tag of the original data of the TWTT clock is aligned with the original data of three ACs, and the statistic of the absence of data is used as the data continuity. Because the current SCB data are estimated daily, data preprocessing is also conducted daily. Then, the phase data are transferred into frequency data (Huang 2018), and the outliers are detected and eliminated by the median absolute deviation (MAD) method. Here is how this method works:

\[
MAD = \frac{\text{Median}\{|y_i - m|/0.6745\}}{0.6745}
\]

where \( m \) is the median of the time series and \( m = \text{Median}\{y_i\} \), and the factor 0.6745 makes the MAD equal to the standard deviation for normally distributed data (Riley 2007). A data point is considered to be an outlier if the observation \( |y_i| > (m + n \cdot \text{MAD}) \) or \( |y_i| < (m - n \cdot \text{MAD}) \), and marked as 0. As mentioned in Riley’s book, integer \( n \) is determined according to needs and using \( n=5 \) is an empirical choice.
Because BDS satellites have mounted rubidium clocks, we select overlapping Hadamard variance to calculate the time-domain stability. Based on the frequency data, the calculation is as follows:

A relative frequency deviation data sequence \( \{y_n, n=1,2,\ldots,M\} \) with a sampling interval \( \tau_0 \) is provided (\( M \) represents the amount of data).

For frequency data, it is defined as:

\[
H \sigma_y^2(\tau) = \frac{1}{6m^2(M-3m+1)} \sum_{j=1}^{M-3m+1} \sum_{i=j}^{j+m-1} [y_{i+2m} - 2y_{i+m} + y_i]^2
\]

(6)

where \( \tau = m\tau_0 \) means the averaging interval, \( m \) represents the averaging factor, which usually takes \( 1 \leq m \leq \text{int}\left(\frac{M}{3}\right) \), and \( y_i \) is the frequency data.

When the periodic characteristics of satellite clock data are analyzed, a spectrum analysis method based on fast Fourier transform (FFT) is adopted. The principle is as follows:

Spectrum analysis mainly takes advantage of waveform characteristics in the form of data. To determine the significant periodic terms, which have large energy (amplitude) characteristics in the spectrum graph, we analyzed the amplitude of the data waveform in the data sequence. According to the special properties of waveforms, the systematic errors in the clock residuals can be considered as data waves with significant periodic terms.

For the discrete Fourier transform (DFT),

\[
X(k) = \sum_{n=0}^{N-1} x(n)e^{-\frac{j2\pi}{N}kn}
\]

(7)

where \( X(k) \) represents the spectrum value of time \( k \); the value of \( x(n) \) corresponds to the residual sequence.

In the actual calculation, FFT is used to solve the problem. In the calculation, the appropriate number of residuals should be selected to make the number satisfy \( N = 2^L \), \( L = 0,1,2\ldots \) If the number does not meet the requirements, elements with a value equal to 0 are added. In this way, the waveform can be improved without affecting the relative size of the spectrum value.

Through the above equation, the spectrum value corresponding to each point in the residual sequence can be obtained, and then the spectrum diagram of the residual sequence can be drawn.

3. Calculation and analysis

We selected a total of 89 days of BDS SCB data from 2018.02.01 to 2018.04.30 to analyze. The ODTS data were downloaded from the website ftp://cddis.gsfc.nasa.gov/pub/gps/products/mgex/, and extracted from precise clock data files named com*.clk, gbm*.clk and wum*.clk of the corresponding time. The TWTT data is post-processed data, which is similar to the final products of IGS. And it is provided by BDS official facility. Its precision has been verified (Liu 2009; Liu 2015; Wang 2018; Gong 2019). Because TWTT data have high accuracy and good consistency, they can be used as both a comparative analysis object and a reference value when calculating the mutual agreement with ODTS data. All the SCB data have the same data sampling interval of 300 seconds.

3.1. Data Continuity

To gauge the continuity of the BDS SCB data provided by CODE, GFZ, WHU and TWTT, we used original, unprocessed data. The data continuity of the 5-min samples is given in Figure 2 and tabulated in Table 1.
Figure 2. Data continuity of each BDS satellite for the period of 89 days. The missing data are blank. The red lines represent TWTT data, the green lines represent CODE data, the blue lines represent GFZ data and the magenta lines represent WHU data. Because CODE does not provide the SCB data of the BDS GEO satellite, its results are all null in the statistics. The x-axis stands for time. The y-axis represents PRN of satellites.

Table 1. Average data missing rate of BDS satellite clocks (%)

| Satellite Type | TWTT | CODE | GFZ  | WHU |
|---------------|------|------|------|------|
| Mean of GEO   | 1.32 | N/A  | 35.13| 5.78 |
| Mean of IGSO  | 22.23| 0.77 | 1.36 | 2.73 |
| Mean of MEO   | 71.81| 0.53 | 1.33 | 1.98 |

According to the statistical results, SCB data of IGSO and MEO provided by CODE have the lowest overall missing rate and the best continuity of corresponding data. Much of the GEO SCB data provided by GFZ is missing, and the maximum missing rate is as high as 50%. However, the SCB data of IGSO/MEO satellites have good data continuity. The overall missing rate of SCB data provided by WHU is relatively balanced, and the missing rate of the GEO satellite is obviously lower than that of GFZ, but the data missing rate of IGSO/MEO satellites is higher than that of the other two ACs. The main possible reasons for this phenomenon are the difference in the number of available satellites as well as the difference in the observation stations involved in the calculation.

The continuity of SCB data provided by CODE, GFZ and WHU shows that the missing rate of the MEO satellite is the lowest, followed by the IGSO satellite and the GEO satellite. The possible reason is that the GEO satellite has relatively frequent orbital maneuvers, which leads to significant anomalies in the multi-satellite orbit determination and satellite clock offset calculation, resulting in the absence of data such as the output of SCB results, and the continuity of SCB data calculated by the GEO satellites based on ODTS is relatively poor. In addition, according to the orbit analysis of the satellite and its track of the sub-satellite point, the spatial distribution and geometric configuration of MEO satellites are better than those of IGSO satellites, which results in more correct and reasonable results of MEO satellites when calculating the orbit and clock based on ODTS. Therefore, the continuity of SCB data of MEO satellites is the best.
The TWTT results show that the data missing rate of GEO satellite data is the least, and its data continuity is much better than that of the products of the three ACs, while the missing rate of MEO satellite data is the highest. As Figure 3 shows, MGEX has deployed satellite-tracking stations around the globe, which is very helpful to obtain continuous data. While TWTT data can only be obtained from the satellite-tracking stations within Chinese territory, which is not a very good geographic coverage for the BDS constellations. Because GEO satellites rarely move dramatically, they can be tracked continuously and have the most continuous data. Only when a satellite experiences an abnormal data period (such as satellite malfunction or uplink disconnection), the TWTT results will be interrupted for a short time, which causes the GEO satellite to suffer from data loss. Due to the limited geographic coverage, when IGSO and MEO satellites move to the other side of the planet (from east to west hemisphere or north to south hemisphere), there is no station can maintain the up-link connection with the satellites. It is the reason that parts of orbital arcs of these two types of satellites will be inevitably untraceable. The data loss rate is proportional to the length of their untraceable arcs.

3.2. Data precision
Figure 4 A quadratic polynomial model is adopted to carry out the overall fitting of the 89-day SCB products and obtain the overall clock fitting residual, which can show the overall trend of the data. The overall fitting residuals of C07 (top panel), C09 (second panel), C11 (third panel), and C14 (bottom panel) using CODE, GFZ, WHU and TWTT data are presented. For reference, the y-axes are set on the same scale. The insets show expanded views of the details in the box.
Because CODE does not provide BDS satellite clock results of GEO satellites, while much of the GFZ data of GEO satellites is missing, we only compared the overall fitting residual results of IGSO and MEO satellites of BDS. As seen from the plots above, the fitting residuals show the same trend, and the variation between the results is small.

TWTT uses pseudorange measurements, while the other three ACs use carrier phase measurements to obtain clock offsets. We can clearly see the difference in Figure 4. The daily residual of TWTT is more scattered than the counterpart of ACs in an epoch-wise manner. Presumably, this is because the noise level of the pseudorange is larger than that of the carrier phase. However, the daily residual of TWTT is steadier from a day’s perspective than the result of ACs.

Moreover, the day-boundary discontinuity phenomenon in the result of CODE is much better than that of the others. The WHU not only has the most significant day-boundary but also has several significant abnormal clock errors in several satellites at the same time. The reason could be the anomalies of time-frequency reference.

The preprocessed daily clock offsets are fitted by quadratic polynomials using the least-square method, and the RMS residuals for each satellite are shown in Figure 5 and tabulated in Table 2.

![Figure 5](image)

**Figure 5** Preprocessed daily clock offsets are fitted by quadratic polynomials using the least-square method, and the RMS residuals of each satellite are presented.

| Satellite Type | TWTT | CODE | GFZ | WHU |
|----------------|------|------|-----|-----|
| Mean of GEO    | 0.46 | N/A  | 0.89| 0.71|
| Mean of IGSO   | 0.36 | 0.65 | 0.67| 0.73|
| Mean of MEO    | 0.26 | 0.30 | 0.47| 0.37|

Among the clocks we analyzed, the result of MEO satellites outperforms GEO and IGSO satellites. There are some variations between different ACs, due to the different data used or different data processing strategy, but the precision is basically at the same level, better than a nanosecond. Additionally, the differences between the three centers are also better than a nanosecond, which shows good consistency between different ACs (Senior K 2008; Wang 2016).

Due to the two-way time comparison mechanism, the majority of orbital errors in the signal propagation link can be eliminated, and thus has less effect to the clock data. The TWTT result has the highest precision, which is better than the counterpart of the three ACs. This finding reveals a very interesting phenomenon. TWTT data is influenced by pseudorange noise, which is larger than carrier phase noise. As Figure 4 shows, the data residual points are more scattered but still have the best
statistical result. This is because the statistic is based on daily results. Under this time scale, the result of ODTS is not as steady as that of TWTT. The amplitude of fluctuation of ODTS is larger than that of TWTT, presumably because orbit error affects the clock data in ODTS data.

In addition, all four kinds of clock offset data show the same level of fitting residuals between the GEO and IGSO satellites, while MEOs have the best fitting precision. This understandably leads to the conclusion that the lower the orbital height is, the less numerous the interferences are in the signal propagation link, and the higher precision of the clock data is.

The data precision of C04, C05 and C06 satellites is over a nanosecond, which is two to three times larger than that of other satellites. The plausible reasons may be related to the decline of satellite clock performance of these three satellites, which affects the stability of satellite clock data.

3.3. External mutual agreement

When analyzing the mutual agreement of different ACs, it is a critical step to remove the influences of different time reference (Sun 2017; Wang 2018). However, it is regarded that the SCB data obtained by ODTS and TWTT is independent from each other. The influence of other parameters, such as TGD (total group delay) can’t be removed. Because of this fact, we take the TWTT data as reference to compare with the clock data of CODE, GFZ and WHU. The variation has been detrended by removing a second-order polynomial. The mutual agreements of them can be obtained by comparative analysis and the results are shown in Figure 6.
Figure 6. Data variations between ODTS and TWTT satellite clock data. The mutual agreement result of CODE (top panel), GFZ (second panel) and WHU (bottom panel) is presented. For reference, the y-axes are set on the same scale. The insets show expanded views of the details in the box.
From Figure 6, if we ignore the discontinuities in the result, we can see the mutual agreement of all three ACs is better than 3ns. There is significant periodic fluctuation in the result of GEO satellites. The periodic fluctuation amplitude of GEO can up to 8ns. Under the assumption that TWTT satellite clock data is relatively less affected by the orbit estimation error, it indicates that satellite clock estimation is affected by satellite orbit error. Due to the different data processing strategy and software implementations, CODE does not provide GEO data, and we can’t measure the periodic fluctuation of its GEO data. However, the day-boundary phenomenon of CODE is better than the counterpart of GFZ and WHU, and this result is consistent with the result of fitting residuals.

Table 3 Mutual agreements between TWTT and ODTS data (ns)

| Satellite Type | PRN | TWTT-CODE | TWTT-GFZ | TWTT-WHU |
|---------------|-----|-----------|----------|----------|
| GEO           |     |           |          |          |
| C01           | N/A | 2.83      | 7.19     |          |
| C02           | N/A | 2.54      | 7.25     |          |
| C03           | N/A | 2.63      | 6.47     |          |
| C04           | N/A | 2.47      | 6.86     |          |
| C05           | N/A | 2.59      | 7.46     |          |
| Mean of GEO   |     | 2.61      | 7.04     |          |
| IGSO          |     |           |          |          |
| C06           |     | 2.28      | 7.05     |          |
| C07           |     | 2.34      | 7.15     |          |
| C08           |     | 2.28      | 7.27     |          |
| C09           |     | 2.37      | 7.21     |          |
| C10           |     | 2.30      | 7.20     |          |
| C13           |     | 2.34      | 7.28     |          |
| Mean of IGSO  |     | 2.31      | 7.19     |          |
| MEO           |     |           |          |          |
| C11           |     | 2.37      | 7.28     |          |
| C12           |     | 2.36      | 7.31     |          |
| C14           |     | 2.28      | 7.12     |          |
| Mean of MEO   |     | 2.33      | 7.23     |          |
| Total Mean Value | 2.32 | 2.40 | 7.15 |

The mutual agreement of TWTT with CODE and GFZ shows similar precision, which is better than 3ns. Because of the day-boundary discontinuity, the statistics of WHU is over 7ns. But in a sub-daily regime, the result is not affected by day-boundary, the mutual agreement of TWTT and WHU is also within 3ns. Despite GEO satellites show obvious periodic fluctuation which characterizes orbit error, the statistics difference between different orbit types is relatively small.

3.4. Data stability analysis based on overlapping Hadamard variance

Considering that all BDS satellites use the rubidium clock, which has significant frequency drift, as a time reference, we selected the overlapping Hadamard deviations (OHDEV) (Baugh R 1971) for time-domain stability analysis using preprocessed SCB data with a sampling interval of 300 seconds. Due to the serious lack of MEO satellite data of TWTT, its results are only used for reference.
Table 4  Time-domain stability analysis of BDS SCB data (10-14 s)

| Satellite Type | PRN  | CODE 10,000s | GFZ 10,000s | WHU 10,000s | TWTT 10,000s |
|---------------|------|--------------|-------------|-------------|--------------|
| GEO           |      |              |             |             |              |
| C01           | N/A  | 7.65         | 5.65        | 6.39        | 1.86         |
| C02           | N/A  | 7.77         | 6.39        | 6.37        | 1.18         |
| C03           | N/A  | 5.87         | 4.55        | 4.37        | 0.80         |
| C04           | N/A  | 16.78        | 10.11       | 10.67       | 2.68         |
| C05           | N/A  | 9.00         | 8.10        | 9.27        | 2.27         |
| Mean of GEO   |      | N/A          | 9.41        | 7.41        | 1.75         |
| IGSO          |      |              |             |             |              |
| C06           | 8.76 | 9.32         | 7.32        | 9.61        | 2.59         |
| C07           | 6.55 | 6.39         | 5.84        | 9.11        | 2.32         |
| C08           | 7.80 | 7.94         | 7.53        | 9.45        | 1.80         |
| C09           | 4.59 | 4.79         | 6.21        | 6.66        | 1.75         |
| C10           | 7.49 | 7.26         | 7.34        | 8.16        | 2.45         |
| C13           | 8.95 | 8.65         | 7.02        | 8.58        | 2.02         |
| Mean of IGSO  |      | 7.36         | 7.39        | 6.87        | 8.60         |
| MEO           |      |              |             |             |              |
| C11           | 4.85 | 5.13         | 4.24        | N/A         | 0.81         |
| C12           | 3.97 | 3.90         | 3.55        | N/A         | 1.11         |
| C14           | 5.62 | 2.91         | 2.72        | N/A         | 1.09         |
| Mean of MEO   |      | 4.81         | 3.98        | 3.50        | N/A          |
| Total Mean Value | 6.51 | 7.38        | 6.18        | 8.05        | 1.77         |
Figure 7 Frequency stability (Overlapping Hadamard deviation) of each BDS satellite is presented. The results of CODE (top panel), GFZ (second panel), WHU (third panel) and TWTT (bottom panel) are presented. For satellite, the legend indicates the PRN code, and orbit type, which red represents GEO, green represents IGSO and blue represents MEO. Because CODE does not provide GEO data of BDS, we only plot other satellites of CODE. In addition, due to a significant data loss of the MEO of TWTT, we only plot other satellites of TWTT. For clarification, the y-axes are set on the same scale.
OHDEV calculated from SCB products with 300s sampling provided by TWTT and ODTS are shown in Figure 7. For averaging time beyond 10,000s, all ODTS products of every BDS satellite display more complex, non-power-law behavior, and a “bump” appears at about 20,000s. This is due to the clock periodic variations and it greatly influence the clock stability over timescales from several hours to 1 day. Moreover, it can be seen that there are no noticeably distinct differences between the individual satellites of different orbit types. But the result of TWTT shows dramatic variations between different satellite orbit types. There is “bump” appears at about 20,000s in every GEO satellite result, but there is no noticeable phenomenon in the result of IGSO satellites.

Among the four different SCB results, the stability of C04, C05 and C06 satellites are relatively poor compared with that of the other satellites, and this result is consistent with the result of fitting residuals. The clocks of these three satellites may suffer from significant performance degradation due to aging or other reasons. C04 and C05 are remarkably affected by random walk frequency modulation (RWFM) noise and present a bump at the averaging time of 1×10^4s, causing it to reach an order of 9-12×10^-14 in the period of 10,000 seconds. The stability of MEO satellites is relatively higher than the counterpart of other satellites. This result is also consistent with the fitting residuals. The lower orbit height of MEO can shorten the distance of time transfer, and cut down the contents that influence precision and stability, thus give MEOs better results. It is also worth mentioning that the stability of C11 satellite shows the characteristic of oscillation, which is obviously different from that of other satellites. It is attributed to the periodic oscillation in the data of C11, as Figure 4 shows, OHDEV estimation will have noise characteristics similar to sinusoidal changes, which will be more severe in a longer averaging time (Guo 2006). The above values are almost the same as the results of Hauschild et al. (2012) and Wang et al. (2016).

From Table 4, relative stability of the BDS satellite clocks can be observed. For the TWTT results, the stability of GEO satellites, which have more continuous observation data, is better than that of the IGSO satellite. For averaging time of 10,000 s, the OHDEV of GEO satellites is about 7.4×10^-14 compared with 8.6×10^-14 for IGSO clocks on average. For the results of CODE, GFZ and WHU, MEO satellites outperform the GEO and IGSO satellite clocks. For averaging time of 10,000 s, the OHDEV of MEO satellites is about 3-5×10^-14 compared with 6-8×10^-14 and 6-10×10^-14, respectively, for IGSO and GEO clocks.

The frequency stability results of the three ACs show a highly identical trend, and the degree of coincidence is relatively high, which shows that the SCB data obtained by ODTS have similar noise characteristics. Both orbit characteristics and the use of carrier phase data have an impact on noise characteristics. In the period of 300 s to 1000 s, TWTT satellite clock is remarkably affected by flicker phase modulation (FLPM) noise. It is suspected the noise of the pseudorange is the main contributing factor.

3.5 Periodic characteristics of BDS clocks

The periodic variation, which is closely related to the orbit-periodic variations, is an important factor affecting SCB data quality. It is suspected the changing of solar illumination due to the orbit-periodic variations will influence satellite internal temperature and thus introduce periodic variations into SCB (Senior K 2008; Montenbruck 2012). In order to identify the periodicity of both TWTT and ODTS data, we use FFT to process the residuals of daily quadratic fitting.
Figure 8  Spectrum analysis of C03 (a), C06 (b), C11 (c) and C14 (d) using FFT are presented. The highest spikes show a major cycle of periodic influences. For clarification, the x-axes represent cycles per revolution, and set on the same scale.

From Figure 8, we can see that there are periodic terms in all four SCB data, especially the ODTS data. GEO and IGSO satellites have significant 12-h (two cycles per revolution or 2 cpr) and 24-h (1 cpr) periodic terms. While for MEO, the result between TWTT and ODTS is different. It can be seen that a significant 1 cpr harmonics in the result of MEO of ODTS. However, there are noticeable 2 to 5 cpr harmonics in the result of MEO of TWTT. It is worth mentioning that a 6.5 cpr and 13 cpr harmonics of C11 can be found. This phenomenon corresponds to the oscillation in time-domain stability analysis. The periodic characteristics in the data are related not only to the solution strategy but also to the satellite orbit type. Wang et al. (2016) investigated the correlations between the harmonic amplitude and the beta angle of the sun above the orbital plane. It is shown that for GEO satellites, which beta angle variations are modest, no apparent correlations can be seen. For IGSO and MEO satellites, the correlations exist and indicate a solar illumination origin for BDS satellite periodic variations.

As the plots show, the amplitude of TWTT is smaller than that of ODTS data, which reveals that TWTT data are also influenced by orbit error, but in a very small degree. As the principle of TWTT shows, it can eliminate most errors during signal propagation. However, there is still some orbit error remains and demonstrates in the SCB data.

4. Summary and Conclusions
Currently, BDS adopts the TWTT method for satellite time synchronization, and due to the regional distribution of system monitoring stations, IGSO and MEO satellite data are seriously lacking. The average data missing rate of GEO satellite data is 1.32%, that of the IGSO satellite is more than 20%, and that of the MEO satellite is over 70%. CODE, GFZ and WHU use the ODTS mechanism, which
has better data continuity in IGSO/MEO satellites. The results show that the MEO satellite has the smallest data missing rate, followed by the IGSO satellite and finally the GEO satellite. Among the three ACs, GFZ has the highest missing rate, and CODE has the lowest.

The data precision of TWTT is better than that of CODE, GFZ and WHU. For TWTT, the fitting residual of the MEO satellite outperforms GEO and IGSO satellite. For the products of the three ACs, slight variation is presented, but the level of fitting residual is equal. The fitting residual of GEO satellites is slightly inferior to that of IGSO satellites, and MEO satellites have the best fitting residual. However, the WHU results show obvious day-boundary discontinuity and abnormal jump in the clock offset data.

The difference between ODTS and TWTT satellite clock data is less than 3ns. The periodic variation of ODTS satellite clock data is related to the satellite orbit estimation error, especially for GEO satellites.

The time-domain stability results of the three ACs are similar, the daily stability of all four data can reach a magnitude of 1×10^{-14}. The TWTT result is remarkably affected by flicker phase modulation (FLPM) noise compared to ODTS result. All BDS satellites display very complex, non-power-law behavior due to the effects of clock periodic variations.

Harmonic period of satellite clock periodic variation obtained from ODTS and TWTT satellite clock data is consistent, and the amplitude of TWTT satellite clock data is less than that of ODTS. The main cycles of GEO and IGSO satellites are 24 h, 12 h and 8 h, while those of MEO satellites are 6 h.

On the whole, the comprehensive data quality of CODE and GFZ is similar, better than that of WHU. Meanwhile, TWTT data has its own unique advantages. Awareness of the data precision, clock stability and harmonic period of TWTT and ODTS data is meaningful to identify the estimation error in different methods. In any future improved BDS clock systems or applications, this would be highly beneficial to merge the advantages of these two types of data for better availability, integrity and accuracy.

Author Biographies
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