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Preliminary Analysis and Evaluation of BDS-3 RDSS Timing Performance

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Abstract: Radio determination satellite service (RDSS) is one of the characteristic services of Beidou navigation satellite system (BDS), and also distinguishes with other GNSS systems. BDS-3 RDSS adopts new signals, which is compatible with BDS-2 RDSS signals in order to guarantee the services of old users. Moreover, the new signals also separate civil signals and military signals which are modulated on different carriers to improve their isolation and RDSS service performance. Timing is an important part of RDSS service, which has been widely used in the field of the power, transportation, marine and others. Therefore, the timing accuracy, availability and continuity is an important guarantee for RDSS service. This paper summarizes the principle of one-way and two-way timing, and provides the evaluation method of RDSS timing accuracy, availability and continuity. Based on BDS-3 RDSS signal measurements of system, the performance of one-way timing and two-way timing is analyzed and evaluated for the first time. The results show that: (1) the accuracy of one-way timing and two-way timing is better than 30 ns and 8 ns respectively, which are better than the official claimed accuracy; (2) the RMS of one-way timing accuracy is 5.45 ns, which is 20% smaller than BDS-2, and the availability and continuity are 100%; (3) the RMS of two-way timing accuracy is 3.59 ns, which is 34% smaller than one-way timing, and both of the availability and continuity are 100%; (4) the orbit maneuver of GEO satellite make the one-way timing has 7.68 h recovery, but has no affection on the two-way timing.

Keywords: BDS-3; RDSS; one-way timing; two-way timing; accuracy; availability; continuity

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1. Introduction

According to the three-step development strategy [1,2], the Beidou navigation satellite system (BDS) has experienced BDS-1 (1990–2003), BDS-2 (2003–2012) and BDS-3 (2016–2020). BDS-3 has started to run formally for the whole world on 31 July 2020, providing the Position, Navigation and Timing service (PNT), Radio Determination Satellite Service (RDSS), Global Short Message Communication (GSMC), Satellite-Based Augmentation Service (SBAS), Precise Point Positioning (PPP), Search and Rescue (SAR), and so on. Among them, RDSS is an important component and a distinctive feature of BDS that has advantages and a competitiveness which are different from Global Positioning Systems (GPS), Global Navigation Satellite Systems (GLONASS) and the Galileo system [3–5].

BDS-2 is composed of fourteen satellites and has provided services since 2012. Among the satellites are five geosynchronous earth orbit (GEO) satellites, five inclined geosynchronous orbit (IGSO) satellites and four medium earth orbit (MEO) satellites. Five GEO satellites can broadcast RDSS signals, and each satellite has two wide beams. BDS-2 RDSS can provide a timing service. The official claimed accuracy of BDS-2 RDSS is 50 ns for the one-way timing service, and 20 ns for the two-way timing service [6,7].

BDS-3 is composed of thirty satellites and has provided services since 2020. Among the satellites are three GEO satellites, three IGSO satellites and twenty-four MEO satellites.

Three GEO satellites can broadcast RDSS signals. In order to improve the capacity of the system, BDS-3 RDSS adopts narrow beams, and each satellite has six narrow beams to provide inbound and outbound links. At the same time, BDS-3 RDSS separates civil signals and military signals, which are modulated on different carriers to improve their isolation, and to realize the security and compatibility. The official claimed accuracy of BDS-3 RDSS is 50 ns for the one-way timing service, and 10 ns for the two-way timing service [6,7].

As a spatial information infrastructure, the availability and continuity of satellite navigation system services are important. Up to now, there are rare existing studies on BDS-3 RDSS timing performances. Based on BDS-3 RDSS signal measurements, this paper analyzed and evaluated the performance of the one-way timing service and two-way timing service for the first time, which provides technical support for RDSS timing application.

2. Materials and Methods

2.1. One-Way Timing Principle

This section describes the basic principle of the RDSS one-way timing service. In the one-way timing process, the user starts a timer at the beginning of a second (the local 1-pps). At the same time, it receives the n-th frame of the outbound signal (which carries a time stamp) transmitted by the central control system (CCS) through the satellite, and uses the time stamp of the n-th frame to stop the timer. Then, the timer measures the time interval Δ_1 [8,9]. The schematic diagram of the one-way timing principle is illustrated in Figure 1.

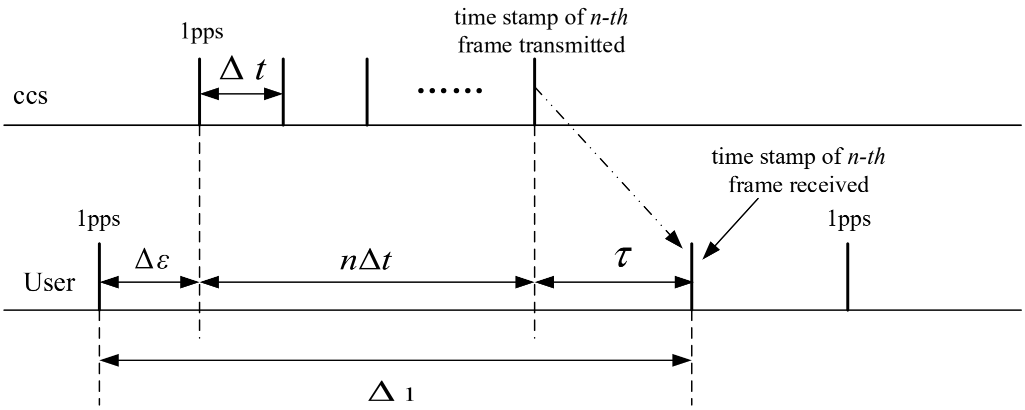

Figure 1. The one-way timing principle.

The clock difference between the user and CCS, denoted by $\Delta\varepsilon$, can be obtained as:

$$\Delta\varepsilon = \Delta_1 - \tau - n\Delta t \quad (1)$$

where Δt = 125 ms is the frame period according to the interface control document (ICD) of the BDS-3 RDSS outbound signal, and τ is the forward propagation delay of the signal, which can be calculated as:

$$\tau = t_{equ} + t_{R01} + t_{R\tau1} \quad (2)$$

where t_{equ} is the one-way time delay of the equipment, which is stored in the user. $t_{R01} = R_{01}/c + t_{R01-pro}$ is the propagation delay from CCS to the satellite; $R01$ is the geometrical distance between CCS and the satellite; c is the light speed; $t_{R01} = R_{01}/c + t_{R01-pro}$ is the ionosphere and troposphere delay, which can be accurately calculated using the parameters broadcast by CCS. $t_{R\tau1} = R_{\tau1}/c + t_{R\tau1-pro}$ is the propagation delay from the satellite to the user; $R_{\tau1}$ is the geometrical distance between the satellite and the user; $t_{R\tau1} = R_{\tau1}/c + t_{R\tau1-pro}$ is the ionosphere and troposphere delay, which is calculated by the user according to the satellite position, user position and broadcast correction parameters [8,9].

From the above Equations (1) and (2), it can be seen that the main factors affecting the accuracy of RDSS one-way timing include GEO satellites' ephemeris errors, ionosphere and troposphere delay correction errors, various equipment delay errors, user position errors, and so on.

2.2. Two-Way Timing Principle

This section describes the basic principle of the RDSS two-way timing service. In a two-way timing process, the user also starts and stops a timer at the start of the local second and at the time stamp of the n-th frame received. What differs is that the forward propagation delay is calculated by CCS and is transmitted to the user. As shown in Figure 2, when the user receives the n-th frame, it sends an inbound signal to CCS immediately. CCS receives the inbound signal, measures the interval Δ_2, and calculates the forward propagation delay τ [8–10], based on Equation (3).

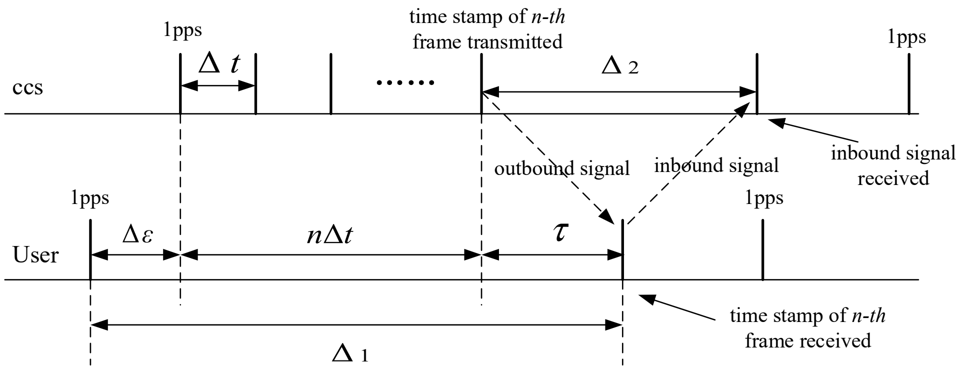

Figure 2. The two-way timing principle.

Assuming that the signal drift of satellite in the process is ignored, the forward propagation delay can be obtained as:

$$\tau = t_{equ\_one-way} + \left(\Delta_2 - t_{equ\_two-way} - t_+ - t_-\right)/2 \quad (3)$$

where $t_{equ\_one-way}$ and $t_{equ\_two-way}$ refer to the equipment time delay of the one-way and two-way (including the time delay of CCS, satellite transmitters and users), Δ_2 refers to the signal round-trip time measured by CCS, t_+ refers to the ionosphere and troposphere delay from CCS to the user through the i-th satellite and t_- refers to the ionosphere and troposphere delay from the user to CCS [8–10].

From the above Equation (3), it can be seen that the main factors affecting the accuracy of RDSS two-way timing include ionosphere and troposphere delay correction errors, various equipment delay errors, and so on. Therefore, the two-way timing accuracy is higher than the one-way timing accuracy. It is worth noting that the signal drift of the satellite in the process is ignored when the forward propagation delay is calculated in Equation (3). However, the drift is related to the speed of motion, which means that periodic fluctuations can also appear in the two-way timing.

3. Results

3.1. Analysis and Evaluation Method

The performance index of BDS-3 RDSS timing service includes timing accuracy, availability and continuity. The analysis methods of each index are described briefly below.

3.1.1. Timing Accuracy

An RDSS receiver, of which its position is known precisely, is used to receive the outbound RDSS signal and then calculate the one-way timing accuracy. Meanwhile, the same receiver is used to send inbound two-way timing signal. CCS will calculate the timing accuracy and compare the results with the known reference 1 pps, which provide a time-frequency reference for the receivers, and measure the timing error of each epoch. The mean value, standard deviation and root mean square (RMS) can be obtained as [8]:

$$\overline{\tau} = \frac{1}{n}\sum_{i=1}^{n}\tau_i \tag{4}$$

$$\mathrm{STD} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}|\tau_i - \overline{\tau}|^2} \tag{5}$$

$$\tau_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}|\tau_i|^2} \tag{6}$$

where τ_i is the discrete point of timing accuracy, n is the number of sample points, $\overline{\tau}$ is the mean value which reflects the constant deviation of timing results, STD is the standard deviation, which reflects the stability and variation range of timing results, τ_{RMS} is RMS, which is the comprehensive result of mean value and standard deviation, and reflects comprehensively the deviation and stochastic error of timing results.

3.1.2. Availability

The availability of the timing service is the time percentage of when the timing accuracy meets the requirements, during the specified period, conditions and service area [6]. For BDS-3 RDSS one-way timing and two-way timing, the accuracy requirements are 50 ns and 10 ns respectively.

Taking the timing error sequence as the evaluation object, the available time percentage of timing service is calculated as:

$$Ava_l = \frac{\sum\limits_{t=t_{start}, inc=T}^{t_{end}} bool\{EPEk \le f_{Acc}\}}{1 + \frac{t_{end}-t_{start}}{T}} \tag{7}$$

where t_{start} and t_{end} is the start time and end time respectively, T is the sampling interval, $EPEk$ is the timing error at a certain time, f_{Acc} is the timing accuracy threshold and $bool\{*\}$ is the Boolean function.

3.1.3. Continuity

RDSS messages are broadcast very second, and the continuity is evaluated without considering the message type. If the receiver receives a message at the current time but it is lost at the next time, it would be recorded as an interrupt, and the interruption duration is the time that receivers cannot receive the message [6].

In order to ensure that the statistical results reflected the messages continuity strictly, three different receivers were used in the experiment. This indicates that an interruption happened only when all three receivers lost the message at the time.

It should be known that the continuity shoud exclude the planned interrupted exception time, which will be published with the warning announcement on the BDS official website, subsequently.

3.2. One-Way Timing Performance Analysis

In order to evaluate the performance of BDS-3 RDSS one-way timing, the following analyses were conducted by the real measured data from the Beijing RDSS receiver. The assessment scenarios included two different states: normal state and satellite orbit maneuver.

3.2.1. Normal State

From 14 February 2021 to 16 February 2021, the receiver collected data from beam two of the BDS-3 C59 satellite. During this period, the satellite was in the normal state, without satellite orbit maneuver or other abnormal status. In this evaluation, the receiver collected timing results for 3 days successively with a 1 s sampling interval, and the one-way timing accuracy curve can be seen in Figure 3.

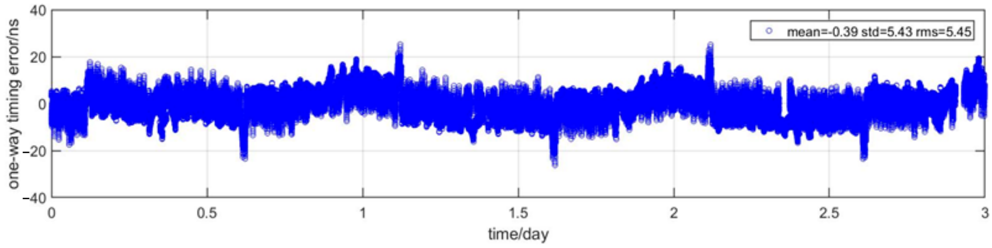

Figure 3. RDSS one-way time service error (normal state).

It can be seen from Figure 3 that: (1) the one-way timing error of all epoch points is less than 30 ns, and the RMS is 5.45 ns, which is 20% smaller than that of the BDS-2 one-way timing error of 6.81 ns [11]; (2) The mean value of one-way timing error is 0.39 ns, which means that there is no significant deviation between the reference 1 pps and the timing results, the equipment delay was calibrated accurately and both ionosphere and troposphere delays were corrected properly; (3) The standard deviation of one-way timing error is 5.43 ns, which actually reflects the white noise in the signal. Moreover, the orbital errors, ionosphere and troposphere delay residual errors always appear as bias.

Furthermore, Figure 3 shows that one-way timing results had a period of 1 day, of which the characteristic was related to the GEO satellite orbit characteristic. In order to further analyze the characteristics of one-way timing error, the spectrum of the one-way timing is shown in Figure 4 and the error removing orbit period is shown in Figure 5.

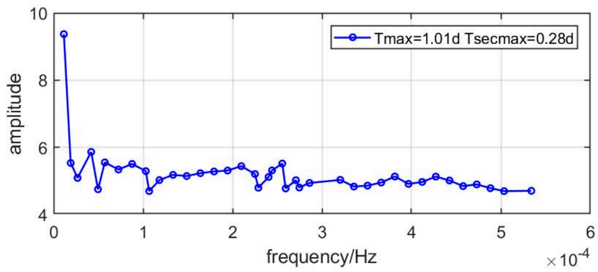

Figure 4. Spectrum analysis results of RDSS time service error.

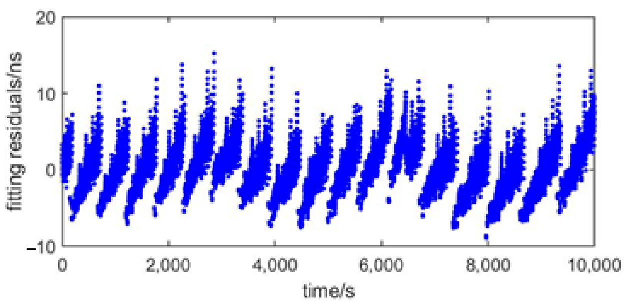

Figure 5. RDSS one-way timing error (remove orbit period).

It can be seen from Figure 4 that the maximum spectrum is 1.01 days (about 24 h 14 m 24 s), which is basically consistent with the orbital period of the GEO Satellite, of 23 h 56 m, and the reason for the inconsistency may be the observation data size and the measurement error. When compared with Figure 3, It can be seen from Figure 5 that the characteristics of the GEO satellite orbital period have been eliminated. However, there is still a periodic jump of the timing error, of which its magnitude is about 10 ns. This phenomenon is related to the RDSS timing principle and the receiver's algorithm. According to the Interface Control Document (ICD), GEO satellite updates the ephemeris every 6 s. Receivers need to interpolate the ephemeris to obtain the satellite position at the timing epoch, and then calculate the timing results based on the fixed point. The interpolation algorithm is the main factor causing the timing error jump.

In order to further evaluate the performance under normal state, the availability and continuity results are given in Table 1. The availability and continuity of the RDSS one-way timing service are 100%.

Table 1. The availability and continuity of one-way timing service (normal state).

Time	14 February 2021	15 February 2021	16 February 2021
Availability	100%	100%	100%
Continuity	100%	100%	100%

3.2.2. Orbit Maneuver State

The ephemeris accuracy of GEO satellites is lower than that of MEO and IGSO satellites due to the orbital characteristics. The orbit of the GEO satellite needs to be adjusted and maintained regularly [12,13]. One-way timing accuracy is mainly limited by orbit determination accuracy during GEO satellite orbit maneuver, because it is related to satellite orbital error. Therefore, the data of one-way timing services were used for analysis and evaluated the orbit maneuver state and recovery of the C59 satellite from 8 February 2021 to 10 February 2021, where the maneuver period was from 11:30 to 13:30 on 8 February 2021.

It can be seen from Figure 6 that: (1) during the orbit maneuver state, the accuracy recovery time of one-way timing is 7.68 h. Specifically, from the start of orbit maneuver, the timing error is within 100 ns about 2.18 h, then the timing error increases to 1000 ns at about 5.08 h and then the timing error gradually decreases and finally returns to the level of 50 ns about 0.52 h. (2) Affected by orbit maneuver, the RMS of the RDSS one-way timing error is 15.33 ns, and its standard deviation is 15.31 ns. This is because in the process of RDSS one-way timing, receivers extrapolate the orbit data according to the ephemeris broadcast by satellites, which is greatly affected by the ephemeris errors of GEO satellites.

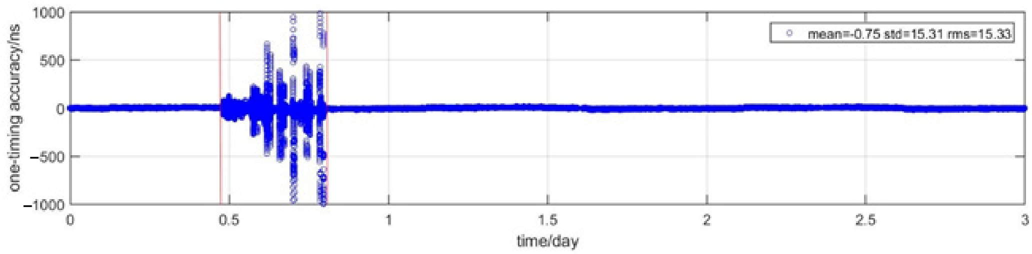

Figure 6. BDS-3 RDSS one-way timing accuracy (orbit maneuver state).

In order to further evaluate the orbit maneuver, the timing accuracy results are given in Table 2. The RMS of normal 8 February, and the recovery on 9 and 10 February are 5.52 ns, 5.49 ns and 5.46 ns, respectively.

Table 2. The accuracy of the RDSS one-way timing service (orbit maneuver state, RMS, unit: ns).

Time	14 February 2021		9 February 2021	10 February 2021
	Normal	Maneuver		
Timing accuracy	5.52	23.21	5.49	5.46

3.3. *Two-Way Timing Performance Analysis*

Similar to the one-way timing, the performance analysis of two-way timing also used the signal measurements from the Beijing RDSS receiver [13]. The assessment scenarios included two different states: normal state and satellite orbit maneuver.

3.3.1. Normal State

From February 14 to 16, 2021, the receiver collected data from beam two of the BDS-3 C59 satellite. During this period, the satellite was in the normal state, without satellite orbit maneuver or other abnormal status. In this evaluation, the receiver adopted timing results for 3 days successively, with z 1 min sampling interval, and the one-way timing accuracy curve can be seen in Figure 7.

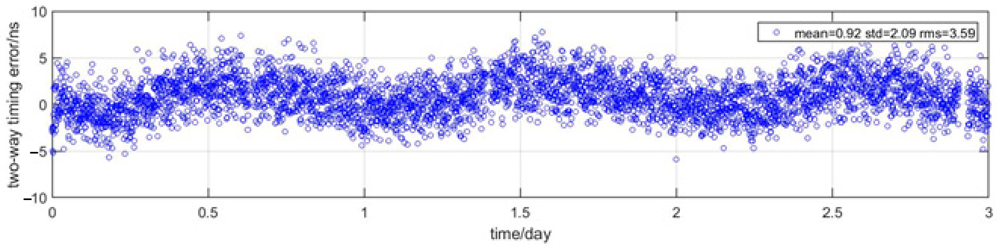

Figure 7. RDSS two-way timing error (normal state).

It can be seen from Figure 7 that: (1) the two-way timing error of all epochs is less than 8 ns, and the RMS is 3.59 ns, which is 34% smaller than that of the one-way timing error of 5.45 ns; (2) the mean value of the two-way timing error is 0.92 ns, which is not much larger than that of the one-way timing of 0.39 ns. This indicates that the equipment delay was calibrated accurately, and both the ionosphere and troposphere delays were corrected properly; (3) The standard deviation is 2.09 ns, which is reduced by 62% when compared with the one-way timing, indicating that GEO satellites orbital errors, ionosphere and troposphere delay errors are greatly reduced in the two-way timing process.

Furthermore, Figure 7 shows that two-way timing results also have a period which is connected to ionosphere and troposphere parameters, which are related to the sun zenith angle, since the GEO satellite is located in geostationary orbit. The spectrum of the two-way timing is shown in Figure 8 and the error removing the orbit period is shown in Figure 9.

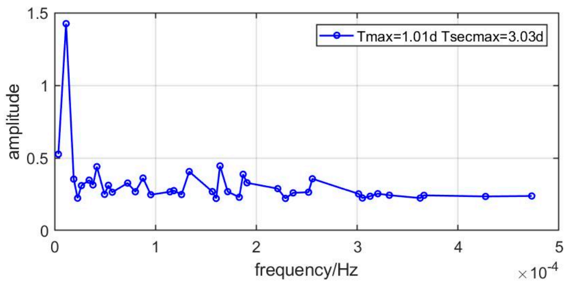

Figure 8. Spectrum analysis results of RDSS timing error.

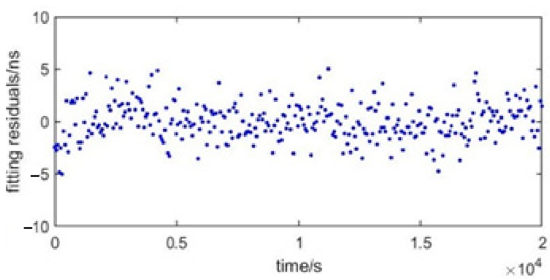

Figure 9. RDSS two-way timing error (remove orbit period).

It can be seen from Figure 8 the maximum spectrum is 1.01 days (about 24 h 14 m 24 s), which is consistent with the analysis results of the one-way timing error series, indicating that the two-way timing is still affected by the GEO satellite orbital error. It is worth noting that the drift is related to the speed of motion, which means that periodic fluctuations can also appear in the two-way timing. When compared with Figure 7, it can be seen from Figure 9 that the characteristics of the GEO satellite orbit period have been eliminated, and there is a 5 ns timing error, which is a comprehensive reflection of the ionosphere and troposphere correction residual errors.

In order to further evaluate the performance under normal state, the availability and continuity results are given in Table 3. The availability and continuity of the RDSS two-way timing service are 100%.

Table 3. The availability and continuity of two-way timing service (normal state).

Time	14 February 2021	15 February 2021	16 February 2021
Availability	100%	100%	100%
Continuity	100%	100%	100%

3.3.2. Orbit Maneuver State

In order to comprehensively analyze the performance of BDS-3 two-way timing, we also analyzed and evaluated the two-way timing results under the orbit maneuvering state. The data was also from 8 February 2021 to 10 February 2021, where the maneuver period was from 11:30 to 13:30 on 8 February 2021.

It can be seen from Figure 10 that the two-way timing under orbit maneuver is consistent with that of the normal state, which means the GEO satellite ephemeris errors were eliminated by the two-way subtraction. Therefore, RDSS two-way timing accuracy has a certain impact on orbit residuals, but it is not obvious. Specifically, the two-way timing error of all epochs during orbit maneuver is smaller than 8 ns, and the RMS, mean value and standard deviation are 3.60 ns, 0.95 ns and 2.07 ns, respectively, which are very close with the results of the normal state. It is worth noting that whether it is maneuvering or not, the GEO satellite moves in the geostationary orbit, and the two-way timing still appears in the periodic fluctuation.

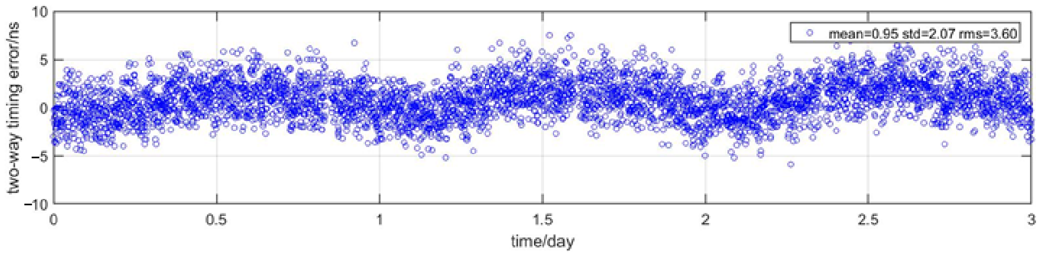

Figure 10. RDSS two-way timing accuracy (orbit maneuver state).

In order to further evaluate the performance of the orbit maneuver state, the availability and continuity results are given in Table 4. The availability and continui ty of theRDSS two-way timing service are 100%.

Table 4. The availability and continuity of two-way timing service (orbit maneuver state).

Time	8 February 2021	9 February 2021	10 February 2021
Availability	100%	100%	100%
Continuity	100%	100%	100%

4. Preliminary Conclusions

This paper discusses the principles of one-way timing and two-way timing, and provides analysis and evaluation methods of timing accuracy, availability and continuity indexes. Using RDSS signal measurements, the performance of BDS-3 RDSS one-way timing and two-way timing were evaluated for the first time under both the normal state and orbit maneuver state. The preliminary conclusions are obtained as follows:

(1) Both one-way timing and two-way timing results are periodical, and the spectrum analysis shows that the period is 1.01 days.
(2) The accuracy of one-way timing is better than 30 ns, and for two-way timing it is better than 8ns.
(3) One-way timing is affected by satellite orbit, while two-way timing is not affected.
(4) The availability and continuity of one-way timing in the normal state are 100%, which cannot be guaranteed in the orbit maneuver state.
(5) The availability and continuity of two-way timing both in normal state and orbit maneuver state are 100%.

In conclusion, the preliminary evaluation results show that the timing performance of BDS-3 is better than the officially claimed one, which can provide technical reference for BDS-3 RDSS users in the normal state and orbit maneuver state.

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