Postprint of On-orbit Performance Evaluation of BeiDou-3 Rubidium Atomic Clocks Based on Satellite-Ground Two-Way Time Comparison Data

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Abstract

Spaceborne atomic clocks are the core equipment of navigation satellites, and their performance directly determines the timing and positioning accuracy of satellite navigation systems. Rubidium atomic clocks are extensively utilized in the BeiDou Navigation System due to their advantages of small size, light weight, low power consumption, and high reliability. This study evaluates the performance of on-orbit rubidium atomic clocks on BeiDou-3 satellites using satellite-ground two-way satellite clock difference data from the BeiDou system. The data processing involved conversion from clock difference to frequency difference and median-based outlier removal, followed by a focused assessment of the rubidium atomic clocks' frequency drift rate and frequency stability. The results indicate that BeiDou-3 rubidium atomic clocks predominantly exhibit negative drift, with a frequency drift rate better than 2 × 10−13 d−1 and a slowly decreasing trend. During the initial operation period, the daily variation magnitude is on the order of 10−15, and after 2 a of operation, the daily drift stabilizes. The calculated thousand-second, ten-thousand-second, and daily stability of the rubidium atomic clocks are approximately 4 × 10−13, 1 × 10−13, and 3 × 10−14, respectively, which differ significantly from ground test results. These results are constrained by noise introduced during the clock difference transmission process and do not reflect the true stability level of the rubidium atomic clocks.

Full Text

Preamble

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Performance Analysis of BD III Satellite Rubidium Atomic Clock Based on Satellite-ground Two-way Time Transfer Data

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Abstract

Space-borne atomic clocks are crucial components of navigation satellites, and their performance directly determines the timing and positioning accuracy of satellite navigation systems. Rubidium atomic clocks are widely used in the BeiDou navigation system due to their small size, light weight, low power consumption, and high reliability. This paper evaluates the performance of rubidium atomic clocks on-board BeiDou-3 satellites using satellite-ground two-way clock offset data from the BeiDou system. The data were first processed by converting clock offset to frequency offset and removing outliers using the median method, followed by a focused assessment of the rubidium atomic clocks' frequency drift rates and frequency stability. The results show that most BeiDou-3 rubidium atomic clocks exhibit negative drift, with frequency drift rates better than 2 (cid:2) 10(cid:0)13 d(cid:0)1, showing a slowly decreasing trend. During the early operation period, the daily variation magnitude is on the order of 10(cid:0)15, and after operating for 2 years, the daily drift tends to stabilize. The calculated stabilities for rubidium atomic clocks are approximately 4 (cid:2) 10(cid:0)13 for 1,000-second stability, 1 (cid:2) 10(cid:0)13 for 10,000-second stability, and 3 (cid:2) 10(cid:0)14 for daily stability. These values differ significantly from ground test results, as the assessment is limited by noise introduced during the clock offset transmission process and does not reflect the true stability level of the rubidium atomic clocks.

Keywords: BeiDou navigation system; space-borne rubidium atomic clock; clock performance evaluation; drift rate; stability
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1 Introduction

Space-borne atomic clocks are the core equipment of navigation satellites, and their performance directly determines the timing and positioning accuracy of satellite navigation systems. Rubidium atomic clocks are widely used in major global satellite navigation systems due to their small size, light weight, low power consumption, and high reliability, with the United States' Global Positioning System (GPS) being the most prominent example. GPS III satellites are equipped exclusively with rubidium atomic clocks, and China's BeiDou-3 system satellites also feature a large number of rubidium atomic clocks. The performance evaluation of on-orbit rubidium atomic clocks has always been an important research topic in satellite navigation. Currently, numerous studies have evaluated the performance of rubidium atomic clocks in the BeiDou system [1{3], most of which employ polynomial models to process and analyze clock offset data to obtain basic information on rubidium atomic clock accuracy, drift rate, and stability performance. However, these studies lack further comprehensive analysis and comparison of the evaluation results.

According to the working principle of atomic clocks, the output frequency of an atomic clock is ultimately locked to the atomic transition frequency. When the atomic transition frequency changes due to physical factors, the output frequency of the atomic clock changes accordingly. If the physical effects causing frequency shifts follow certain patterns over time, these patterns will be directly reflected in the clock's output frequency changes. Therefore, frequency offset data has clearer physical meaning and is easier to model, and analyzing frequency offset data facilitates further evaluation of rubidium atomic clock performance characteristics. In contrast, clock offset represents the cumulative effect of relevant patterns over time, making modeling more complex. Consequently, in atomic clock performance evaluation, we typically analyze frequency offset data.

This paper is based on BeiDou-3 system satellite-ground two-way clock offset data. First, the data are converted to frequency offset data, then processed and analyzed, followed by an evaluation of on-orbit rubidium atomic clock performance, and finally, the relevant results are analyzed and discussed.

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2 Clock Offset Data Preprocessing Methods

Clock offset data preprocessing consists of two main steps: first, converting clock offset data to frequency offset data through time differentiation, and then eliminating outliers and jumps in the frequency offset data. The primary challenge in this process is accurately identifying and removing outliers and jumps. Currently, the most commonly used method for outlier removal is the median absolute deviation (MAD) method [4]. However, when data changes monotonically over time, directly applying the median method for preprocessing typically only removes larger outliers and jumps. To better eliminate data outliers, the monotonic term can first be removed from the data to obtain residuals, and then the median method can be used to identify the positions of outliers in the residuals, finally removing the corresponding outliers from the original data. This approach has been employed in references [2] and [5].

The processing method used in this paper is as follows: first, the frequency offset data are averaged 10 times according to the sampling time; then, a linear fitting method is used to remove the monotonic variation term from the frequency offset; and finally, the median method is applied to eliminate outliers and jumps in the frequency offset data.

3 Rubidium Atomic Clock Performance Evaluation Method

The relative frequency deviation of a rubidium atomic clock output can be expressed as:

$$y(t) = a_0 + a_1(t) + "(t)$$

where a_0 represents the deviation of the atomic clock from its nominal frequency (typically 10 MHz or 5 MHz) at a given time, characterized by accuracy; $a_1(t)$ represents the directional change in the clock's relative frequency offset over time interval t, reflecting the clock's frequency drift characteristics; and $"(t)$ represents the uncertainty in the clock's relative frequency offset over time interval t, associated with random noise in the atomic frequency discrimination signal within the clock, commonly evaluated using frequency stability. For normally operating space-borne rubidium atomic clocks, the focus of performance evaluation is on frequency drift rate and frequency stability, which respectively determine the variation pattern of accuracy and its uncertainty range.

Drift rate evaluation is typically achieved by fitting long-term frequency data to certain mathematical models. For rubidium atomic clocks, the drift rate can be approximated as linear drift over short periods, and the drift rate can be solved using the least squares method.

Frequency stability is commonly characterized by the Allan variance of the relative frequency offset [6]. When the atomic clock's output frequency exhibits directional drift, the Allan variance cannot accurately reflect the atomic clock's frequency stability. For rubidium atomic clocks, it is often necessary to employ numerical methods to first remove the drift term from the frequency data according to a specific mathematical model, and then evaluate frequency stability using the frequency residuals. Additionally, using Allan variance to assess atomic clock frequency stability requires uninterrupted sampling of test data. However, the satellite-ground clock offset data for BeiDou medium Earth orbit (MEO) satellites is intermittent, and directly using this data for evaluation introduces bias between the obtained frequency stability and the true value, requiring correction. This paper adopts the method from reference [7] to correct the evaluation results.

4 Performance Evaluation Results

The BeiDou-3 system includes 12 satellites with rubidium atomic clocks as primary clocks, all of which are MEO satellites. Relevant details are presented in Table 1 . The rubidium atomic clocks on satellites 46 49 were developed by the Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences (hereafter referred to as "the Academy"). For simplicity, satellite numbers in the following text refer to the corresponding satellite's rubidium atomic clock.

This paper uses BeiDou system satellite-ground two-way clock offset phase data from January 1 to March 31, 2020, as the raw data. The data are converted to frequency offset data using the method described in Section 2, and then the performance of BeiDou-3 on-orbit rubidium atomic clocks is evaluated using the method from Section 3. Specific results are presented below.

4.1 Drift Characteristics

This paper uses the daily frequency drift rate (daily drift) to characterize the frequency drift characteristics of rubidium atomic clocks. To comprehensively evaluate drift characteristics, this paper calculates a daily drift using frequency offset data with a measurement duration of 17 days, meaning that when calculating the daily drift for day i, continuously measured frequency offset data from day $(i-16)$ to day i are used. The daily drift rates of each rubidium atomic clock and their variation over time are shown in Figure 1 [Figure 1: see original paper].

Overall, except for the rubidium atomic clock on satellite 36, the remaining 11 rubidium atomic clocks all exhibit negative daily drift. We note that GPS system space-borne rubidium atomic clocks also predominantly show negative drift characteristics [8], and rubidium atomic clocks developed by the Academy also exhibit negative drift during ground vacuum environment testing, which should be related to the working principle of rubidium atomic clocks themselves. The daily drift values of each rubidium atomic clock at the end of March 2020 are presented in Table 2 . From the specific daily drift values, the absolute values of daily drift for all rubidium atomic clocks are better than 2×10^{-13}, with the rubidium atomic clock on satellite 36 achieving a daily drift better than 1×10^{-14}, approaching that of on-orbit hydrogen clocks [2].

Based on the temporal variation trend of daily drift, the rubidium atomic clocks can be divided into three groups: satellites 48 and 49 as Group 1, satellites 38 43, 46, and 47 as Group 2, and satellites 36 and 37 as Group 3. The daily drift for Groups 1 3 corresponds to Figures 1a), b), and c), respectively.

Group 1 clocks show relatively rapid changes in daily drift over time, with the daily drift of clock 48 also exhibiting fluctuations. Group 2 clocks show slowly decreasing daily drift, with daily variations of approximately 3×10^{-16}. Group 3 clocks have stabilized drift rates. The following analysis examines this phenomenon.

Numerous factors contribute to rubidium atomic clock frequency drift, such as pumping light intensity attenuation [9], helium permeation in the atomic vapor cell [10], diffusion of buffer gas molecules in the cell toward the cell walls [11], and aging of electronic components. Currently, no definitive conclusion indicates which factor plays a decisive role. Based on different physical mechanisms, models for rubidium atomic clock output frequency variation over time include exponential, diffusion, and logarithmic models [12], corresponding to drift caused by pumping light intensity attenuation, gas diffusion in the atomic cell, and electronic component aging, respectively. The specific expressions are as follows:

Exponential model:

$$y = a + b \times \exp(t = c)$$

Diffusion model:

$$y = a + b \times (t + c)$$

Logarithmic model:

$$y = a \times \ln(b \times t + 1)$$

where a, b, and c are constants, and t represents time.

All three models indicate that rubidium atomic clocks exhibit larger frequency drift rates during initial operation, which gradually stabilize after some time. The three models show significant differences during the initial stable operation period of rubidium atomic clocks. Since the space-borne clocks on satellites 48 and 49 have relatively short operation times and have not yet reached a stable state, their drift rate changes remain unstable. Therefore, this paper uses frequency offset data from satellites 46 and 47, which are in the initial stable operation period, for fitting analysis according to the above models. The fitting results show that the frequency offset variation over time agrees well with the diffusion model, preliminarily indicating that gas diffusion within the atomic cell may be the primary factor affecting the drift of these rubidium clocks. Specific results are shown in Figure 2 [Figure 2: see original paper].

Note: The scatter plot shows frequency offset data after outlier removal and smoothing over 600 s, while the solid line represents the fitted curve.

Relative frequency deviation variation over time for space-borne rubidium atomic clocks on satellites 46 and 47

Based on the fitting results in Figure 2, it can be inferred that during the initial stable operation period of this rubidium atomic clock, daily drift changes are on the order of 10^{-15} per day. After one year of continuous stable operation, daily drift changes are on the order of 10^{-16} per day, and after two years of continuous operation, daily drift changes are approximately 10^{-17} per day.

According to these results, we believe that Group 3 clocks have been operating for more than 2 years, with daily drift changes on the order of 10^{-15} within 90 days. Compared with the rubidium atomic clock's own drift rate (10^{-13} d^{-1}), this is negligible, and the drift rate of Group 3 clocks can be considered stable within this timescale. Group 2 clocks have mostly been operating for 1 2 years, with daily drift changes on the order of 10^{-14} within 90 days, thus still showing slowly varying daily drift within this timescale.

4.2 Stability Performance

Before evaluating rubidium atomic clock stability, we first remove the drift term from the frequency offset data to obtain the residual term, and then evaluate the stability of the residuals using the method described above. Specific results are shown in Figure 3 [Figure 3: see original paper] and Table 3 .

The stability evaluation results show that the 1,000-second frequency stability of each satellite's rubidium atomic clock mostly falls between $(3-4) \times 10^{-13}$, the 10,000-second stability is approximately 1×10^{-13}, and the daily stability is approximately 3×10^{-14}. From the stability curves, the 10 1,000-second stability of each rubidium atomic clock versus sampling time basically follows a $3 \times 10^{-10} = (cid : 28)$ relationship, which is limited by white phase noise. The 10,000-second to daily stability of each rubidium atomic clock versus sampling time basically follows a $1 = (cid : 28)$ relationship, with similar white frequency noise limitations for each rubidium atomic clock, all approximately $1 \times 10^{-11} = (cid : 28)$.

Note: Hollow dot-dashed lines represent on-orbit clock stability curves, solid dot-dashed lines represent stability curves for space-borne clocks 46 and 47 during ground testing, short dashed lines represent the $3 \times 10^{-10} = (cid : 28)$ *stability curve, and long dashed lines represent the* $1 \times 10^{-11} = (cid : 28)$ *stability curve.*

Figure 3: Frequency stability curves of BeiDou-3 space-borne rubidium atomic clocks

Table 3: Frequency stability evaluation results for space-borne rubidium atomic clocks

Since rubidium atomic clocks 46 49 were developed by the Academy, Figure 3 also presents the stability results of these clocks during ground vacuum environment testing, which differ significantly from the above evaluation results. The analysis is as follows.

We believe that although the above stability evaluation results objectively reflect the stability of satellite-ground clock offset, they do not represent the true stability level of the satellite rubidium atomic clocks. There are two main reasons. First, satellite-ground clock offset data introduces various types of noise during transmission [13], which degrades the stability of satellite-ground clock offset but does not indicate deterioration in the satellite clock's inherent stability. The noise introduced during transmission of primary and backup clock phase comparison data on board the satellite is relatively small; therefore, using phase comparison data allows for more accurate assessment of satellite clock stability performance. Reference [14] used phase comparison data to evaluate the stability of BeiDou-3 satellite clocks, showing that rubidium atomic clocks achieve 1,000-second stability better than 4×10^{-14}, 10,000-second stability better than 2×10^{-14}, and daily stability mostly better than 1×10^{-14}. Second, the frequency offset data for rubidium atomic clocks on satellites 48 and 49 had relatively low noise levels during February 11 20, 2020 (corresponding to days 41 50 in Figure 4 [Figure 4: see original paper]). Using data from this period, we obtained better stability evaluation results, as shown in Figure 5 [Figure 5: see original paper], with nearly a two-fold improvement in 1,000-second and 10,000-second stability performance. It should be noted that although the rubidium clock operation state was not yet stable at this time, this has minimal impact on the accuracy of short- to medium-term stability evaluation; therefore, the results in Figure 4 are reliable. Since satellite clock frequency stability cannot have large fluctuations, we can conclude that the 1,000-second and 10,000-second stability of this satellite clock are at least better than 1×10^{-13} and 3×10^{-14}, respectively.

Frequency stability curves of rubidium atomic clocks on satellites 48 and 49

5 Summary and Discussion

This paper evaluates the frequency drift rate and stability performance of on-orbit rubidium atomic clocks using BeiDou two-way satellite-ground clock offset data, obtaining drift rate and stability evaluation results as of March 31, 2020, presented in Table 2. The main results are as follows:

(1) The absolute daily drift of BeiDou-3 on-orbit rubidium atomic clocks is better than 2×10^{-13}, with most exhibiting negative drift. The drift rate of rubidium atomic clocks changes slowly over time, with its absolute value showing a decreasing trend.

(2) The diffusion model can satisfactorily explain the slowly varying phenomenon of rubidium atomic clock drift rates. The study also shows that during the initial on-orbit operation period, daily drift changes are on the order of 10^{-15} per day. After one year of continuous stable operation, daily drift changes are on the order of 10^{-16} per day, and after two years of operation, the rubidium atomic clock drift rate stabilizes.

(3) Based on satellite-ground clock offset evaluation, the on-orbit rubidium atomic clocks achieve approximately 4×10^{-13} for 1,000-second stability, 1×10^{-13} for 10,000-second stability, and 3×10^{-14} for daily stability. These values differ significantly from ground test results, and we conclude that they do not reflect the true stability level of the rubidium atomic clocks.

Based on the above results, the following points warrant discussion:

(1) Considering the slowly varying characteristic of rubidium atomic clock drift rates, appropriate models must be selected for clock offset prediction over daily timescales. Currently, some literature on long-term clock offset prediction for the BeiDou system uses only a quadratic model, treating the frequency drift rate of space-borne clocks as constant. However, for rubidium atomic clocks, especially those with operation times less than 2 years, this prediction method introduces biases, and the resulting research findings may be inaccurate. Further investigation is needed on the specific impacts. We propose using logarithmic or diffusion models for long-term clock offset prediction.

(2) The stability evaluation results of satellite-ground clock offset are limited by noise introduced during the satellite-ground clock offset transmission process, indicating that the performance of on-orbit rubidium atomic clocks is not fully realized. Research on reducing this noise could help improve the timing and positioning accuracy of the BeiDou-3 system.

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

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