

## Article

# Atomic Clock Performance Assessment of BeiDou-3 Basic System with the Noise Analysis of Orbit Determination and Time Synchronization

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**Abstract:** The basic system of the BeiDou global navigation satellite system (BDS-3) with 18 satellites has been deployed since December 2018. As the primary frequency standard, BDS-3 satellites include two clock types with the passive hydrogen maser (PHM) and the rubidium atomic frequency standard (RAFS). Based on the final precise orbit and clock product from Xi'an Research Institute of Surveying and Mapping (XRS), the atomic clock performance of BDS-3 satellites is evaluated, including the frequency accuracy, frequency drift rate, and frequency stability, and compared with GPS block IIF satellites with RAFS, Galileo satellites with PHM, and BDS-2 satellites. A data auto-editing procedure to preprocess clock data and assess the clock performance is developed, where the assessed results are derived at each continuous data arc and the outliers are excluded properly. The stability of XRS product noise is given by using some stations equipped with high-precision active hydrogen masers (AHM). The best stability is  $8.93 \times 10^{-15}$  and  $1.85 \times 10^{-15}$  for the averaging time of 10,000 s and 1 day, which is basically comparable to one-third of the in-orbit PHM frequency stability. The assessed results show the average frequency accuracy and drift rate of BDS-3 with RAFS are slightly worse while the stability is better than BDS-2 medium earth orbit (MEO) satellites. The 10,000 s stability is better but the 1-day stability is worse than GPS, which may be related to the performance of the BDS-3 RAFS clock. As for BDS-3 with PHM, the frequency accuracy is slightly worse than Galileo PHM satellites; the drift rate, when excluding C34 and C35, is basically comparable to Galileo and significantly better than GPS satellites; the stability is comparable to Galileo, where the 10,000 s stability is slightly worse than Galileo and better than GPS. The 1-day stability among BDS-3 PHM, GPS IIF RAFS, and Galileo PHM satellites is basically comparable.

**Keywords:** BDS-3; Clock performance; PHM; RAFS; Hadamard deviation

## 1. Introduction

The BeiDou navigation satellite system (BDS) provides positioning, navigation, and timing (PNT) service with high continuity, reliability, and stability for global users. The high-precision and stable in-orbit atomic clock plays a key role in global satellite navigation system (GNSS) positioning and navigation. With increasing Beidou-3 satellites equipped with the passive hydrogen maser (PHM) and rubidium atomic frequency standard (RAFS) orbiting in space, the clock performance needs to be explored. Particularly, the clock stability has a significant influence on PNT service. By the end of December 2018, there were 18 medium earth orbit (MEO) satellites and 1 geostationary earth orbit (GEO) satellite in orbit, which form the BDS-3 basic system and mainly serve counties in the

China-proposed Belt and Road Initiative. The public signals include B1C, B2a, B2b, and the old BDS-2 signals, B1I and B3I [1]. Table 1 lists the satellite information [2], where the GEO satellite C59 with RAFS is still under testing status.

**Table 1.** BDS-3 satellite information.

SVN	PRN	Common Name	Sat. ID	Manuf.	Launch Date	Status
C201	C19	MEO-1	2017-069A	CAST	5 November 2017	USABLE
C202	C20	MEO-2	2017-069B	CAST	5 November 2017	USABLE
C203	C27	MEO-7	2018-003A	SECM	11 January 2018	USABLE
C204	C28	MEO-8	2018-003B	SECM	11 January 2018	USABLE
C205	C22	MEO-4	2018-018A	CAST	12 February 2018	USABLE
C206	C21	MEO-3	2018-018B	CAST	12 February 2018	USABLE
C207	C29	MEO-9	2018-029A	SECM	29 March 2018	USABLE
C208	C30	MEO-10	2018-029B	SECM	29 March 2018	USABLE
C209	C23	MEO-5	2018-062A	CAST	29 July 2018	USABLE
C210	C24	MEO-6	2018-062B	CAST	29 July 2018	USABLE
C211	C26	MEO-12	2018-067A	SECM	24 August 2018	USABLE
C212	C25	MEO-11	2018-067B	SECM	24 August 2018	USABLE
C213	C32	MEO-13	2018-072A	CAST	19 September 2018	USABLE
C214	C33	MEO-14	2018-072B	CAST	19 September 2018	USABLE
C215	C35	MEO-16	2018-078A	SECM	15 October 2018	USABLE
C216	C34	MEO-15	2018-078B	SECM	15 October 2018	USABLE
C217	C59	GEO-1	2018-085A	CAST	1 November 2018	TESTING
C218	C36	MEO-17	2018-093A	CAST	18 November 2018	USABLE
C219	C37	MEO-18	2018-093B	CAST	18 November 2018	USABLE

BDS-2 has been studied by many scholars, including the precise orbit determination (POD) [3,4], modeling of solar radiation pressure [5], attitude mode [6], positioning performance [7,8], and signal characteristics [9]. In the initial period of BDS-2 providing service, Gong et al. [10] used four estimation strategies to analyze the short-term stability with the best satellite C09 located in inclined geosynchronous orbit (IGSO) being  $4 \times 10^{-13}$  and  $1 \times 10^{-13}$  at 100 s and 1000 s averaging time, respectively. Then, further studies of BDS-2 clock performance were analyzed by many researchers to assess the frequency stability [11–16]. The clock data were derived mainly by the orbit determination and time synchronization (ODTS) method. Montenbruck et al. [11] gave the initial result, and the stability of BDS-2 RAFS satellites with 1 and 1000 s averaging time was  $0.1 \sim 7 \times 10^{-12}$  and  $1 \sim 3 \times 10^{-13}$ , while for GPS IIF satellites it was  $4 \sim 6 \times 10^{-12}$  and  $1 \times 10^{-13}$ , respectively. Steigenberger et al. [12] used different POD strategies to assess the performance of BDS-2 clocks, and the stability at the averaging time of 1000 s for GEO and IGSO satellites was  $8 \sim 12 \times 10^{-14}$  and  $8 \sim 17 \times 10^{-14}$ , respectively, which is better than the result of [11]. Then, Wang et al. [13] used the clock product from Wuhan University with 5 min sampling rate to assess the BDS-2 clock performance. The Allan deviation (ADEV) of GEO, IGSO, and MEO clocks was about  $3 \sim 5 \times 10^{-13}$ ,  $3 \sim 8 \times 10^{-13}$ , and  $2 \sim 4 \times 10^{-13}$  at the averaging time of 300 s, which is comparable to the reference [14]. When the averaging time was 10,000 s, the ADEV was  $8 \sim 11 \times 10^{-14}$ ,  $6 \sim 12 \times 10^{-14}$ , and  $4 \sim 6 \times 10^{-14}$ , correspondingly. Also, the two-way satellite time and frequency transfer (TWSTFT) data was analyzed by Zhou et al. [15]. Huang et al. [16] gave the detailed analysis of the long-term in-orbit situation of BDS-2 clocks with a length of about five years.

Two IGSO and two MEO experimental satellites of BeiDou-3 were launched between 2015 and 2016. Technologies of the signal system [17], intersatellite links [18], and POD [19] were validated and analyzed. The atomic clock performance was also assessed with the clock data derived by the TWSTFT [20] or ODTS method [21,22]. Wu et al. [20] analyzed the frequency stability, prediction accuracy, and clock rate variation, and the optimal stability at the averaging time of 86,400 s is  $6.5 \times 10^{-15}$  for the IGSO satellite C32 with the Ka-band measurement noise of  $3 \times 10^{-15}$ . Zhao et al. [21] gave an initial result with the regional distribution of ground stations. The stability of IGSO satellite clocks at 1000 s averaging time is  $2 \sim 4 \times 10^{-14}$ , which is 10 times better than that of BDS-2 satellites.

Lv et al. [22] analyzed the stability, periodicity, and prediction precision of BDS-3e clocks. The 10,000 s stability of C32 with PHM is  $2.6 \times 10^{-14}$ , which is comparable to Galileo PHM and GPS IIF RAFS. As for the BeiDou-3 full operational capability (FOC) satellites, Yan et al. [23] gave the early results with 11 BDS-3 MEO satellites during DOY 142–145 of 2018, which showed the 10,000 s stability is  $2 \sim 5 \times 10^{-14}$ . Xu et al. [24] used 26 d observation data from about 100 Multi-GNSS Experiment (MGEX) and the international GNSS Monitoring and Assessment Service (iGMAS) stations [25] during DOY 030–059 in 2019 to assess the stability of BDS-3 satellite clocks. The POD adopted the one-step method with the arc of three days. The averaged 10,000 s and 86,400 s stability for BDS-3 satellite clocks was  $2.43 \times 10^{-14}$  and  $2.51 \times 10^{-15}$ , respectively. However, the ODTS noise was not given quantitatively. Comparable stability of the PHM and RAFS seemed to be derived. Besides, Guo et al. [26] gave the Hadamard derivation (HDEV) results of BDS-3 clock stability directly.

This study analyzes the performance of BDS-3 satellite clocks with the ODTS noise given quantitatively. First, methodology is introduced. The ODTS product from Xi'an Research Institute of Surveying and Mapping (XRS) [27] is introduced and compared to the Wuhan University product (WUM) and the IGS final product. Then, the ODTS noise is calculated by a few ground stations which are attached to the high-precision active hydrogen masers (AHM). Afterwards, the performance of BDS-3 satellite clocks is assessed in terms of frequency accuracy, frequency drift rate, and frequency stability. Finally, the conclusion is given.

## 2. Methodology

The frequency accuracy of the atomic clock is defined as:

$$\sigma = \frac{f - f_0}{f_0} \quad (1)$$

where  $\sigma$  denotes the frequency accuracy,  $f$  the actual frequency, and  $f_0$  the nominal frequency. Equation (1) describes the absolute concept of the frequency accuracy, which is not derived directly in actual data processing. Generally, the frequency accuracy is calculated by the time difference method, that is, the phase difference between two consecutive epochs is obtained:

$$y_i = \frac{x(t_1 + v) - x(t_1)}{v} \quad (2)$$

where  $x$  is the clock (phase) data,  $v$  the data sampling interval, and  $y_i$  the frequency data at epoch  $t_i$ . With the phase data in a long time series, the frequency accuracy can be obtained by calculating the mean value of the differenced data series. It should be noted here that Equation (2) is also the formula of converting the phase data to frequency data. The frequency drift rate can be written as:

$$D = \frac{\sum_{i=1}^N (y_i - \bar{y}) \cdot (t_i - \bar{t})}{\sum_{i=1}^N (t_i - \bar{t})^2} \quad (3)$$

where  $D$  denotes the frequency drift rate and  $N$  the number of  $y_i$ .  $\bar{y}$  and  $\bar{t}$  denote the mean value of  $y_i$  and  $t_i$ , respectively. The evaluation of frequency stability usually uses the ADEV or HDEV method. The Allan deviation is the most common time domain measure of frequency stability [28], but it is sensitive to the linear drift of the frequency data. Hence, we choose the HDEV method to evaluate the frequency stability. The HDEV examines the second difference of the frequency data and is insensitive to the linear frequency drift. The formula reads:

$$\sigma_y^2(\tau) = \frac{1}{6(M-2)} \sum_{i=1}^{M-2} (\gamma_{i+2} - 2\gamma_{i+1} + \gamma_i)^2 \quad (4)$$

where  $y_i$  denotes the  $i$ th of  $M$  fractional frequency values with the averaging time  $\tau$  [28].

With the above formulas and the ODTS clock products, the frequency accuracy, drift rate, and stability of the atomic clock can be derived by a data processing procedure. For one clock data series, the steps are as follows:

1. The clock differenced data between the clock data of one station or one satellite and reference clock data (AHM station) are derived, named as phase data. The sampling interval is 300 s.
2. The preprocessing of data editing is completed on a daily basis. If the data loss rate on a given day (i.e., the percentage between the lost epochs and the sum of epochs (288)) is more than 20%, this day is flagged as an unavailable day. If the phase data on a given day are available, the linear interpolation method is used to fill the phase data for those lost data on a daily basis.
3. The phase data of one day are converted to the frequency data by the first-order time difference. Then, with the frequency data, the outliers, the phase jumps, and the frequency jumps are detected and removed by using the median absolute deviation (MAD) method:

$$\theta = \text{Median}\left(\frac{|y_i - \text{Median}(y_i)|}{0.6745}\right) \quad (5)$$

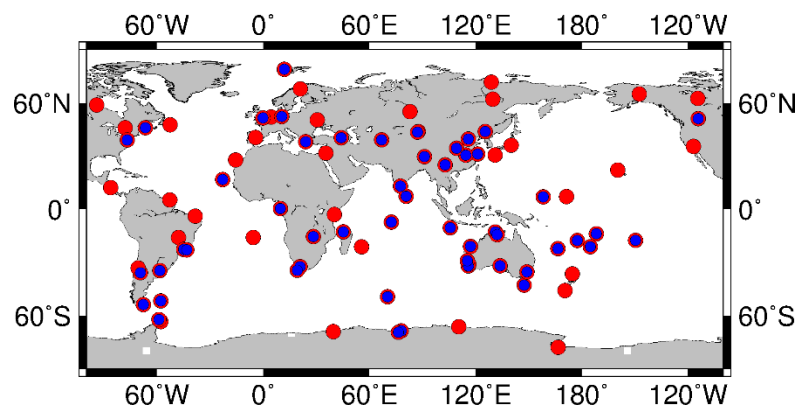
where  $y_i$  is the frequency value and the  $\text{Median}(y_i)$  denotes the median value of the time series of  $y_i$ .  $\theta$  denotes the sigma of the median deviation under the condition of normal distribution. Five times  $\theta$  is regarded as the threshold to reject the bad data (i.e., if  $|y_i| > \text{Median}(y_i) + 5 \cdot \theta$ , then  $y_i$  is treated as an outlier) [28].

4. The lost days are counted and flagged, and then the data are fragmented. If the number of days in a continuous segment is less than seven, these data are deleted. There exists the day boundary value between two consecutive days. Thus, the connection point value is deleted and retrieved by using the linear interpolation method. Then, the clean frequency data can be derived.
5. With the clean frequency data in a continuous arc, the performance of atomic clocks can be calculated, including the frequency accuracy, frequency drift rate (daily), and frequency stability (300 s, 9900 s, and 86,400 s). The HDEV is used to characterize the frequency stability. In the following text, the stability at the averaging time 9900 s is denoted as 10,000 stability.
6. Repeat step 5 for the next data arc, and then the clock assessed results can be derived in the next continuous arc. With the frequency accuracy, drift rate, and stability of each continuous arc, the average values of all arcs can be derived, which is the final assessed result of one atomic clock.

### 3. Precise Orbit and Clock Product Introduction and Analysis

In order to validate that the XRS product is competent to evaluate space clock stability, the XRS product precision is first analyzed. The multi-GNSS XRS precise orbit and clock product is calculated by the software Satellite Positioning and Orbit Determination System (SPODS) [27]. About 80 MGEX stations and 20 iGMAS stations with GPS, BDS, Galileo, and GLONASS satellite data are used to process precise orbit determination, including ultrarapid (XRU), rapid (XRR), and final (XRS) products in the daily routine. The BDS-3 observations are from B1I and B3I signals. Figure 1 shows the used ground stations, where there are about 50 stations tracking BDS-3 signals (i.e., the blue circles). With orbit and clock products from XRS, WUM, and IGS, the series of difference values between the orbits of two precise products on each day in radial (R), along-track (T), cross-track (N), and three-dimensional (3D) directions are computed. Then, the root mean square (RMS) of the difference values series is derived with the reference frame differences being eliminated by using Helmert transformation. As for the clocks, the RMS and STD are computed with the time series difference values between two precise products. Table 2 gives the averaged orbit RMS in R, T, N, and 3D directions and the RMS and STD of clocks over the processing time period. “GPS(XRS)” and “GPS(WUM)” denote the results of XRS and WUM compared with IGS products, respectively. The results of Galileo and BDS satellites are calculated by comparing XRS products with WUM products.





**Figure 1.** Ground station distribution of XRS POD products, where the blue circles denote stations that can track BDS-3 signals.

**Table 2.** Averaged values of comparison results of XRS and WUM products.

	Orbit [m]				Clock [ns]	
	R	T	N	3D	RMS	STD
GPS(XRS)	0.0115	0.0132	0.0146	0.0233	0.242	0.051
GPS(WUM)	0.0127	0.0121	0.0132	0.0225	0.198	0.052
Galileo	0.0183	0.0241	0.0296	0.0431	0.338	0.085
BDS-2-GEO	0.394	1.353	1.024	1.742	–	1.31
BDS-2-IGSO	0.103	0.340	0.343	0.494	–	0.16
BDS-2-MEO	0.115	0.213	0.230	0.334	–	0.14
BDS-3-RAFS	0.118	0.225	0.242	0.351	–	0.17
BDS-3-PHM	0.119	0.209	0.215	0.322	–	0.21

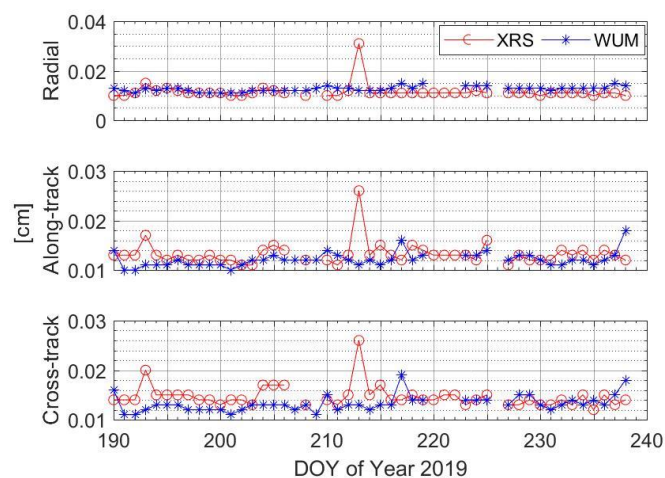
Figure 2 shows the daily averaged RMS of all GPS satellites in R, T, and N directions for XRS and WUM products compared with IGS products. The orbit accuracy of XRS and WUM is basically consistent, with the RMS in R and 3D directions being about 1.2 and 2.3 cm, respectively. The RMS of XRS products in radial direction is slightly better than that of WUM products, while in T and N directions, it is slightly worse. Figure 3 presents the RMS and STD of the clock comparison results. The STD of XRS products is slightly better than that of WUM products, while the RMS is slightly worse, with the RMS and STD for XRS products being about 0.24 and 0.05 ns, respectively. The GPS comparison results show the XRS product is excellent and comparable to the IGS analysis center.

Figure 4 presents the comparison results of Galileo satellites between XRS and WUM products. The accuracy of the two products is consistent, with the orbit RMS in R, T, N, and 3D directions being 1.8, 2.4, 3.0, and 4.3 cm, respectively, and the clock RMS and STD being 0.34 and 0.08 ns, respectively.

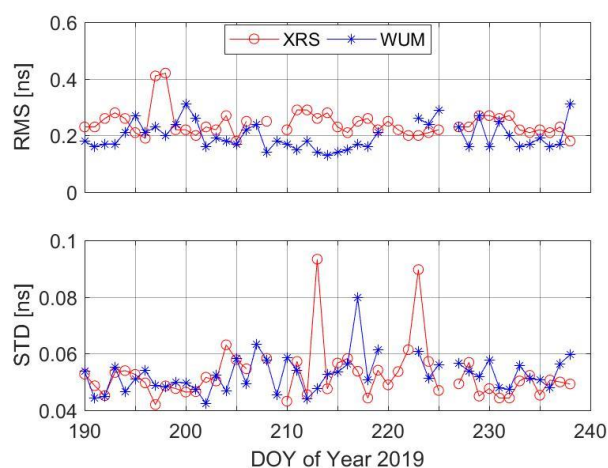
Figures 5 and 6 show the orbit and clock comparison results of BDS-3 satellites between XRS and WUM products. The orbit 3D RMS of BDS-2 GEO satellites is at meter level, while for IGSO and MEO, it is at 3 and 4 decimeter levels, respectively. The STD of clocks is about 0.2 ns. The orbit RMS in R and 3D directions is 0.118 and 0.351 m for BDS-3 RAFS satellites and 0.119 and 0.322 m for BDS-3 PHM satellites, respectively. The clock STD of BDS-3 RAFS and PHM is 0.17 and 0.21 ns, respectively. The clock STD of C34 and C35 with PHM is 0.33 and 0.48 ns, respectively, while the mean value of other PHM satellites is 0.14 ns. Besides, the clock and orbit accuracy of C37 is relatively bad, with clock STD of 0.36 ns and orbit 3D RMS of 0.53 m. The specific reason needs to be further studied.

Compared with the results of GPS and Galileo, the orbit and clock of BDS satellites are worse, especially the RMS of clocks. Hence, the RMS of clocks is not listed in Table 1. The possible reasons are as follows. First, for BDS-2 satellites, the antenna phase center product is inconsistent, where XRS uses the reprocessed products [29] and WUM may use the products released by Wuhan University [30] or IGS product [31]. The antenna phase center offsets of BDS-3 satellites are also not absolutely equal.

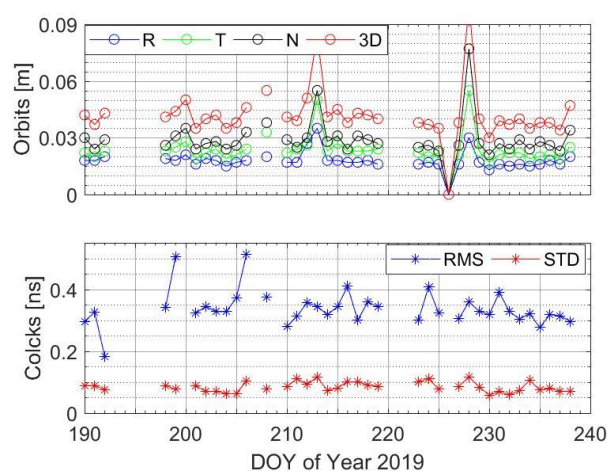
Then, the important reason may be the difference of POD strategies for the two products. The third reason is that BDS-3 satellites are running in orbit for only about half a year, and the work of error and model refinement is still being studied.



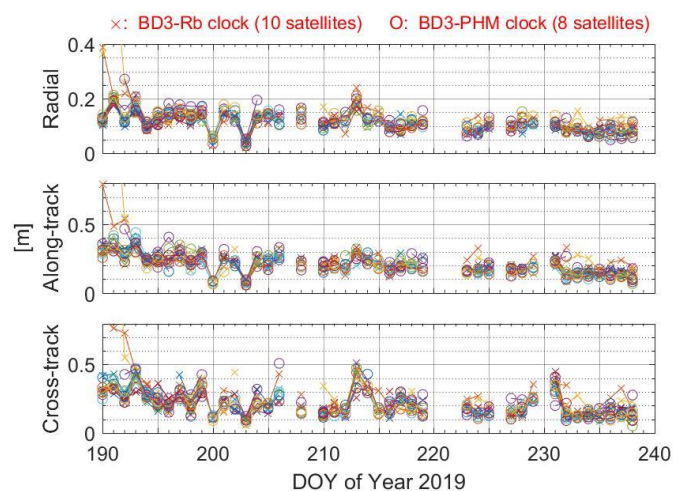
**Figure 2.** GPS orbit results of XRS and WUM compared with IGS products.



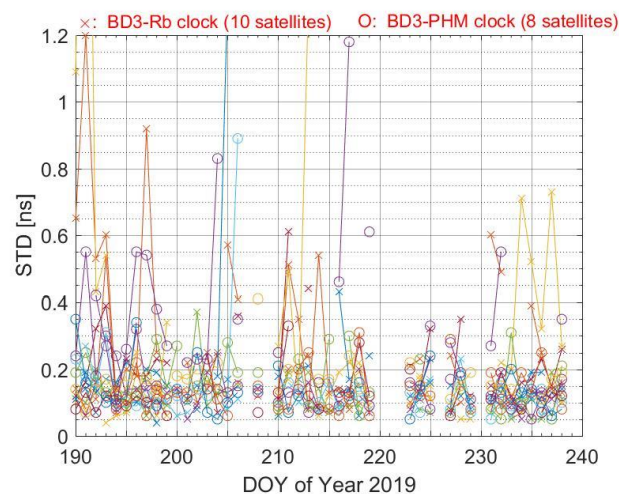
**Figure 3.** GPS clock offset results of XRS and WUM compared with IGS products.



**Figure 4.** Galileo orbit and clock offset results of XRS products compared with those of WUM products.



**Figure 5.** BDS-3 orbit results of XRS products compared with those of WUM products, where  $\times$  indicates 10 BDS-3 satellites with RAFS and  $\circ$  indicates 8 BDS-3 satellites with PHM.



**Figure 6.** BDS-3 clock offset results of XRS products compared with those of WUM products.

#### 4. Noise Analysis of ODTs

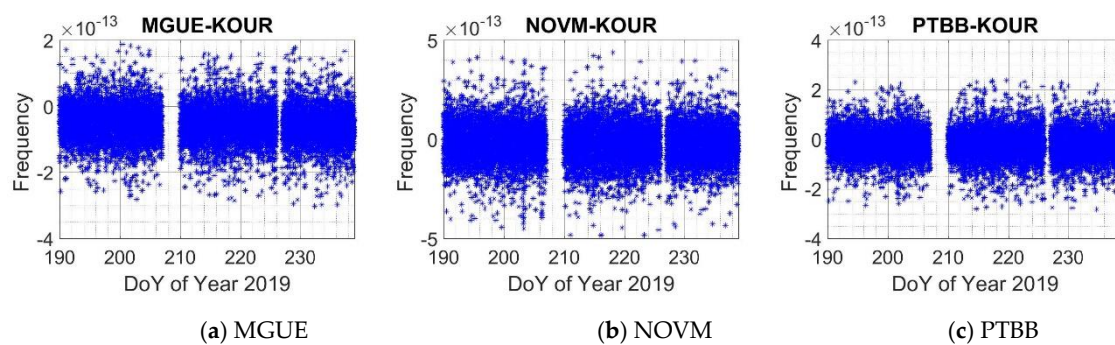
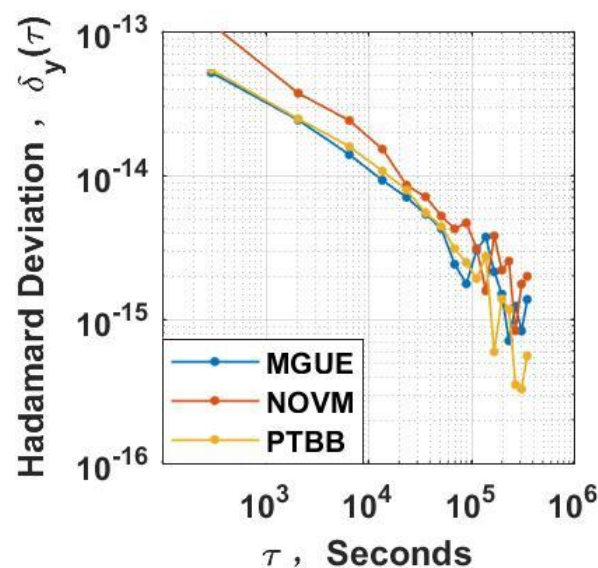
The test assessment methods of GNSS satellite clocks include the phase comparison approach, the radio two-way method, the orbital inverse algorithm, and the prevailing ODTs method. The ODTs method uses the observation data from global ground stations with high-precision carrier phase measurements, and undoubtedly, a systematic noise exists in ODTs products. These errors include the measurement error, the ionospheric delay, the tropospheric delay, the multipath effect, the dynamic model, and the influence of ground station distribution. Hence, the systematic noise of ODTs needs to be quantified before assessing the performance of GNSS satellite clocks. The high-precision orbit and clock products of IGS, XRS, and WUM are derived by the ODTs method, where there are some ground stations attached to high-stability AHM. Therefore, we can calculate the frequency stability of ODTs noise by differencing receiver clocks of two stations attached to high-stability AHM. Table 3 shows some stations' information used in XRS products.

**Table 3.** Some stations attached to high-stability AHM.

Station	Location	Country	Type	Input frequency	Valid period
PTBB	Braunschweig	Germany	AHM	20 MHz	28 January 2010~
KOUR	Kourou	French Guiana	AHM	10 MHz	20 November 2012~
MGUE	Malargue	Argentina	AHM	10 MHz	28 October 2013~
NOVM	Novosibirsk	Russia	AHM	5 MHz	24 July 2001~

The time period from July 9 to August 26 in 2019 was chosen to assess the ODS noise. The differenced values between one receiver clock of three stations (PTBB, MGUE, and NOVM) and the KOUR station were derived. Figure 7 shows the frequency offsets of the differenced values after processing the data editing procedure. It can be seen that the outliers or jumps are basically removed.

Figure 8 shows the HDEV of one continuous arc frequency data as the function of averaging time. Results of three curves are comparable, though station NOVM is slightly worse than the other two stations. Table 4 gives the statistics of ODS noise for the three stations. The tiny HDEVs at averaging time 10,000 s and 86,400 s show the consistency of receiver clocks between two ground stations attached to AHM. The average values are about  $1.13 \times 10^{-14}$  and  $2.68 \times 10^{-15}$  for 10,000 s and 86,400 s frequency stability, respectively.

**Figure 7.** Frequency offsets of the differenced values between one receiver clock of three stations and KOUR station.**Figure 8.** HDEV of the differenced frequency data for the three stations with respect to KOUR station.

**Table 4.** Statistics of ODTS noise.

Station Diff.	Accuracy	Drift Rate	Stability		
			300 s	10,000 s	1 Day
MGUE-KOUR	$5.66 \times 10^{-14}$	$4.70 \times 10^{-16}$	$5.26 \times 10^{-14}$	$8.93 \times 10^{-15}$	$1.85 \times 10^{-15}$
NOVM-KOUR	$2.29 \times 10^{-14}$	$2.48 \times 10^{-16}$	$1.11 \times 10^{-13}$	$1.41 \times 10^{-14}$	$3.14 \times 10^{-15}$
PTBB-KOUR	$2.18 \times 10^{-14}$	$2.56 \times 10^{-16}$	$5.69 \times 10^{-14}$	$1.09 \times 10^{-14}$	$3.04 \times 10^{-15}$
Averaged value	$3.38 \times 10^{-14}$	$3.25 \times 10^{-16}$	$7.35 \times 10^{-14}$	$1.13 \times 10^{-14}$	$2.68 \times 10^{-15}$

## 5. Performance Assessment of BDS-3 Satellite Clocks

Based on the information of satellite table [32,33], Table 5 lists the pseudo-random noise (PRN) and the corresponding clock type of GNSS satellites. The processing period is from DOY 190 to 238 in 2019, which is consistent with the assessment period of ODTS noise. During this period, the BDS-2 included 5 GEO, 7 IGSO, and 3 MEO satellites, with the clock type being RAFS. The BDS-3 basic system included 10 MEO satellites with RAFS, 8 MEO satellites with PHM, and 1 GEO satellite with RAFS, where the GEO satellite was excluded due to the testing status during this period. We only chose the GPS block IIF satellites with RAFS and Galileo IOV and FOC satellites with PHM. Hence, there were 10 GPS satellites and 21 Galileo satellites.

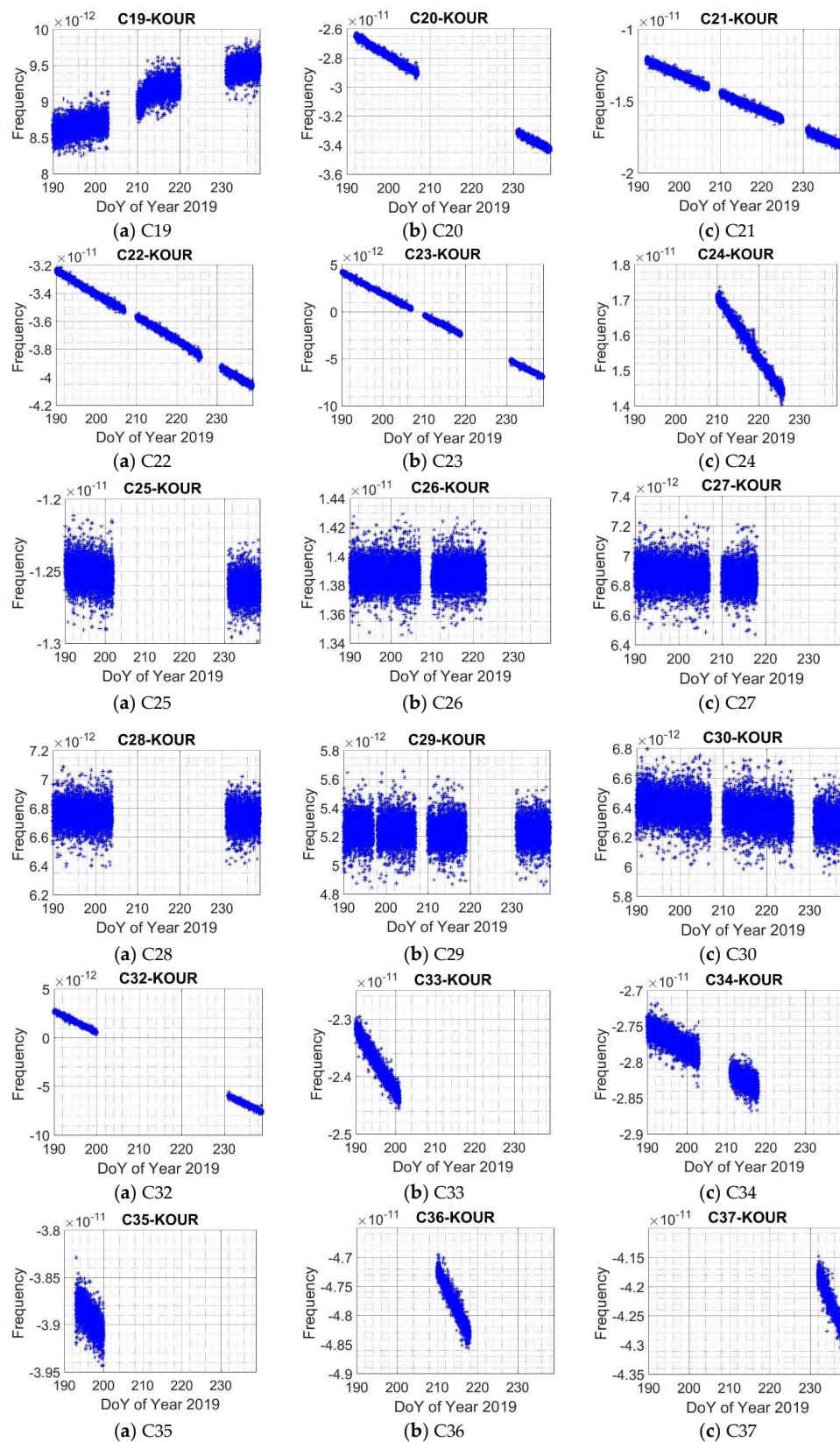
**Table 5.** GNSS satellite PRN and clock type used in the analysis.

GNSS	Satellite Type	PRN	Clock Type
BDS-2	GEO	C01 C02 C03 C04 C05	RAFS
	IGSO	C06 C07 C08 C09 C10 C13 C16	
	MEO	C11 C12 C14	
BDS-3	MEO	C20 C21 C22 C23 C24 C32 C33 C36 C37	RAFS
	MEO	C25 C26 C27 C28 C29 C30 C34 C35	PHM
GPS	IIF	G01 G03 G06 G09 G10 G25 G26 G27 G30 G32	RAFS
Galileo	IOV	E12 E19	PHM
	FOC	E01 E02 E03 E04 E05 E07 E08 E09 E13 E15 E21 E24 E25 E26 E27 E30 E31 E33 E36	

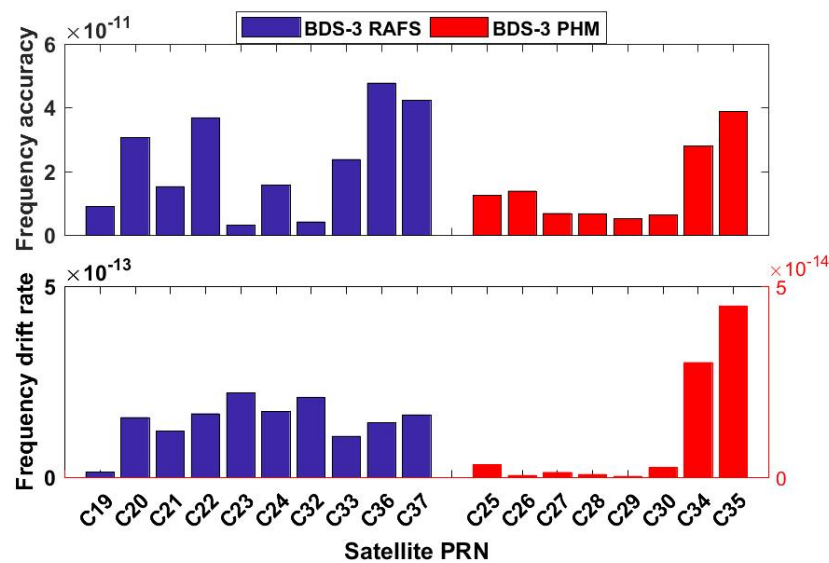
### 5.1. Results

The differenced data between the clock data of one GNSS satellite and the receiver clock of the ground station KOUR attached to the high-precision AHM were derived. Then, the data editing procedures were completed, as described in Section 2. Figure 9 presents the clean frequency data of each BDS-3 satellite, where we see there are almost no jumps or outliers. Then, the BDS-3 atomic clock performance was derived. Figure 10 is the averaged frequency accuracy and frequency drift rate during the whole assessment period. It can be seen that the frequency accuracy of BDS-3 PHM is slightly better than BDS-3 RAFS, while the frequency drift rate is significantly superior. The frequency drift rate of BDS-3 with PHM when excluding C34 and C35 is  $1.44 \times 10^{-15}$ , which is about two orders of magnitude better than that of BDS-3 RAFS satellites, showing the good performance of the PHM clock. Figure 11 gives the averaged frequency stability with the averaging time of 300 s, 10,000 s, and 86,400 s. The stability is basically comparable among BDS-3 satellites with the same clock type. The HDEV is basically comparable between BDS-3 RAFS and PHM satellites at the averaging time of 300 s, while the stability of 10,000 s and 86,400 s for BDS-3 PHM is better than BDS-3 RAFS, especially the 1 d stability.

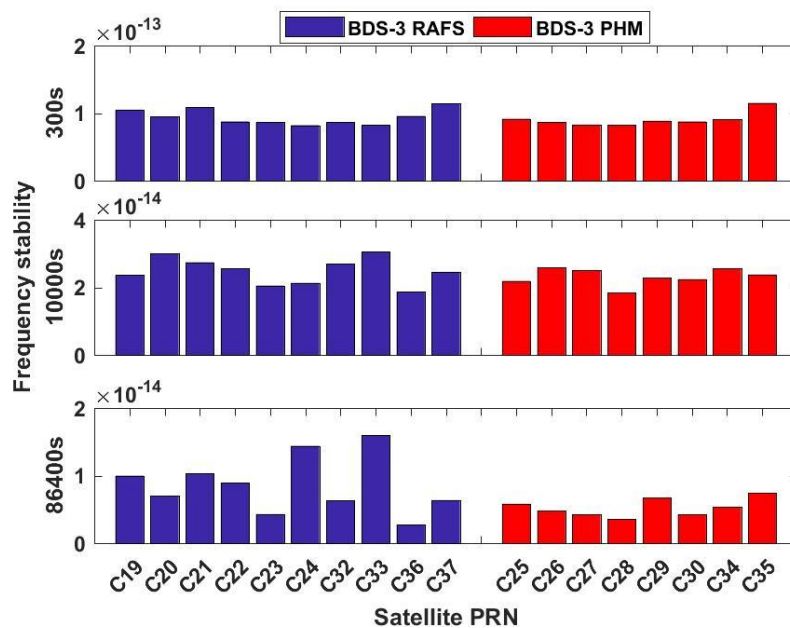




**Figure 9.** Frequency offsets of the differenced values between BDS-3 satellite clocks and KOUR station clocks.

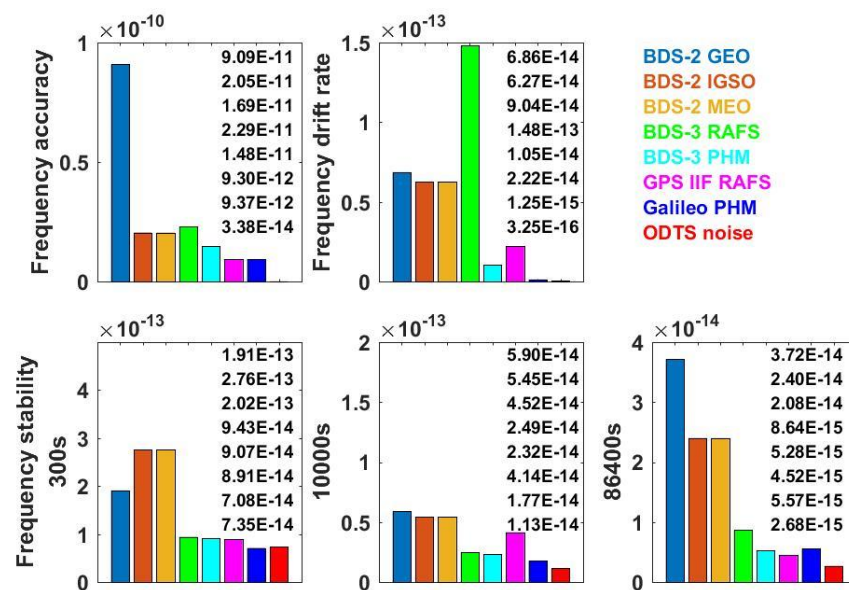


**Figure 10.** Averaged frequency accuracy and frequency drift rate during the whole assessment period for BDS-3 RAFS and PHM satellites. Note the y-axis of frequency drift rate for BDS-3 PHM is on the right side.



**Figure 11.** Averaged frequency stability with the averaging time of 300 s, 10,000 s, and 86,400 s for BDS-3 RAFS and PHM satellites.

Figure 12 summarizes the results of GNSS clock assessment in terms of the frequency accuracy, drift rate (daily), and stability at the averaging time 300 s, 10,000 s, and 86,400 s, during the data processing period. The frequency accuracies of BDS-3 RAFS and PHM are  $0.3\sim 4 \times 10^{-11}$  and  $0.5\sim 3 \times 10^{-11}$ , with the average values of  $2.29 \times 10^{-11}$  and  $1.48 \times 10^{-11}$ , respectively, while for GPS satellites with RAFS, it is  $0.2\sim 1 \times 10^{-11}$  and the average value is  $9.30 \times 10^{-12}$ . Correspondingly, the frequency accuracy of Galileo satellites with PHM is  $9.37 \times 10^{-12}$  with a large variation range of  $3 \times 10^{-14}\sim 4 \times 10^{-11}$ . The averaged frequency accuracies of BDS-2 GEO, IGSO, and MEO satellites with RAFS are  $9.09 \times 10^{-11}$ ,  $2.05 \times 10^{-11}$ , and  $1.69 \times 10^{-11}$ , respectively, which is comparable to the results of [34]. The average accuracy of BDS-3 with PHM is slightly worse than that of the GPS and Galileo satellites, while the accuracy of BDS-3 with RAFS is basically comparable to the BDS-2 IGSO and MEO satellites.



**Figure 12.** Overall atomic clock performance for different types of GNSS satellites, including the frequency accuracy, drift rate, and stability.

In terms of the daily frequency drift rate, the result of BDS-3 with RAFS is  $0.1\sim 2 \times 10^{-13}$  with an average value of  $1.48 \times 10^{-13}$ . Only C19 is in the order of  $1 \times 10^{-14}$ , while other RAFS satellites are about  $1\sim 2 \times 10^{-13}$  with a small variation. The range of BDS-3 with PHM is  $3 \times 10^{-16}\sim 4 \times 10^{-14}$  with an average value of  $1.05 \times 10^{-14}$ . C34 and C35 with PHM are relatively bad with the values of  $3.01 \times 10^{-14}$  and  $4.49 \times 10^{-14}$ , respectively, which are worse by at least one order of magnitude than the other PHM satellites. The drift rate of GPS satellites is about  $0.7\sim 4 \times 10^{-14}$  with an average value of  $2.22 \times 10^{-14}$ , and the difference among GPS satellites is small. The drift rate of Galileo satellites is about  $0.2\sim 3 \times 10^{-15}$  with an average value of  $1.25 \times 10^{-15}$ , which presents the best result and is comparable to the result of [35]. The average drift rates of BDS-2 GEO, IGSO, and MEO satellites are  $6.86 \times 10^{-14}$ ,  $6.27 \times 10^{-14}$ , and  $9.04 \times 10^{-14}$ , respectively, which are comparable to the results of [34]. The results of C03, C04, C06, C16, and C14 are in the order of  $1 \times 10^{-13}$ , which are relatively worse than the other satellites. The frequency drift rate of BDS-3 with RAFS is basically comparable to BDS-2 MEO satellites and worse than GPS IIF satellites, while that of BDS-3 with PHM, except C34 and C35, is slightly worse than Galileo PHM satellites.

In terms of the stability with the averaging time of 300 s, the result of BDS-3 RAFS is about  $0.8\sim 1 \times 10^{-13}$  with an average value of  $9.43 \times 10^{-14}$ , and similarly, the result of BDS-3 PHM is about  $0.8\sim 1 \times 10^{-13}$  with an average value of  $9.07 \times 10^{-14}$ . The stability of GPS satellites is about  $8\sim 9 \times 10^{-14}$  with an average value of  $8.91 \times 10^{-14}$ , and for Galileo satellites, it is  $6\sim 7 \times 10^{-14}$  with an average value of  $7.08 \times 10^{-14}$ . The average result of BDS-3 PHM satellites is slightly worse than GPS and Galileo. The stability of BDS-2 GEO, IGSO, and MEO satellites is  $1.91 \times 10^{-13}$ ,  $2.76 \times 10^{-13}$ , and  $2.02 \times 10^{-13}$ , respectively, showing BDS-3 RAFS is better than BDS-2 satellites. BDS-3 RAFS is slightly worse than GPS IIF RAFS satellites.

In terms of the stability of the averaging time of 10,000 s, the range of BDS-3 RAFS satellites is  $2\sim 3 \times 10^{-14}$  with an average value of  $2.49 \times 10^{-14}$ . Almost all satellites are smaller than  $3 \times 10^{-14}$ , which is better than that of GPS satellites with an average value of  $4.14 \times 10^{-14}$  and variation range of  $2\sim 6 \times 10^{-14}$ . The stability of BDS-2 GEO, IGSO, and MEO satellites is  $5.90 \times 10^{-14}$ ,  $5.45 \times 10^{-14}$ , and  $4.52 \times 10^{-14}$ , respectively, which is better than the results of [13] with the 10,000 s stability being about  $8\sim 11 \times 10^{-14}$ ,  $6\sim 12 \times 10^{-14}$ , and  $4\sim 6 \times 10^{-14}$ , respectively. It can be seen that the result of BDS-3 RAFS is better than that of BDS-2 satellites. The 10,000 s stability of BDS-3 PHM is  $1\sim 2 \times 10^{-14}$  with an average value of  $2.32 \times 10^{-14}$ , which is slightly worse than that of Galileo satellites with an average value of  $1.77 \times 10^{-14}$  and variation range of  $1\sim 2 \times 10^{-14}$ .

In terms of the stability with the averaging time of 86,400 s, the range of BDS-3 RAFS satellites is  $0.2 \sim 1 \times 10^{-14}$  with an average value of  $8.64 \times 10^{-15}$ , which is worse than the stability of GPS satellites with an average value of  $4.52 \times 10^{-15}$  and variation range of  $3 \sim 6 \times 10^{-15}$ . The stability of GPS is comparable to the result of [34] with an average value of  $5 \times 10^{-15}$ . The variation range of 86,400 s stability for BDS-3 PHM satellites is  $3 \sim 7 \times 10^{-15}$  and the average value is  $5.28 \times 10^{-15}$ , which is slightly better than the average value of  $5.57 \times 10^{-15}$  for Galileo satellites with the range of  $0.2 \sim 1 \times 10^{-14}$ . The stability of BDS-2 GEO, IGSO, and MEO satellites is  $3.72 \times 10^{-14}$ ,  $2.40 \times 10^{-14}$ , and  $2.08 \times 10^{-14}$ , respectively, which is comparable to the results of [34].

## 5.2. Discussion

In order to analyze the specific characteristic of stability during the whole averaging time, Figure 13 gives the HDEV of one continuous arc for BDS-2 satellites. It can be seen that there are significant periodic signals at the time of about 2 cycles per revolution (cpr) with 12 h, while this phenomenon is not obvious for BDS-3, GPS, and Galileo satellites, as shown in Figures 14 and 15. The stability of C16 is significantly better than other BDS-2 IGSO satellites, and the launch date of C16 was on 2018/07/09. From Figures 13 and 14, we see the stability of BDS RAFS has a significant improvement from BDS-2 to BDS-3, and the BDS PHM presents the best clock stability. Figure 15 shows the stability of E07 and E08 is relatively worse than other Galileo satellites, with the average values being  $0.76 \times 10^{-14}$  and  $1.91 \times 10^{-14}$  for the averaging time of 86,400 s. The average value of other Galileo satellites is  $4.67 \times 10^{-15}$ . In general, the stability at the averaging time of 86,400 s for BDS-3 PHM, GPS IIF RAFS, and Galileo PHM satellites is comparable.

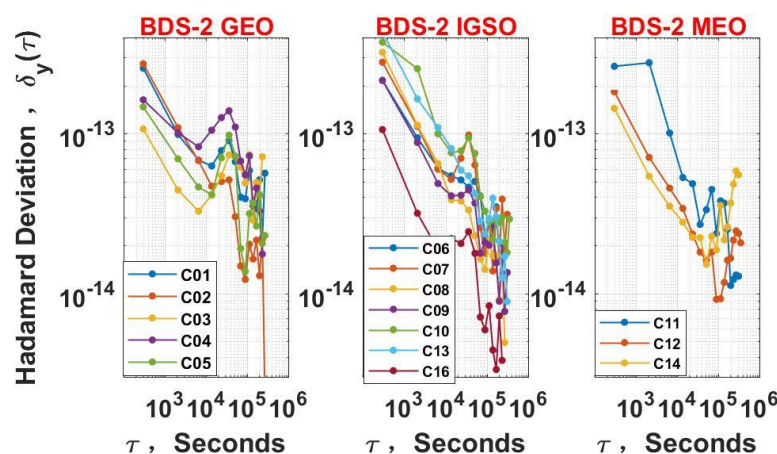


Figure 13. HDEV of the differenced frequency data for BDS-2 satellites with respect to KOUR station.

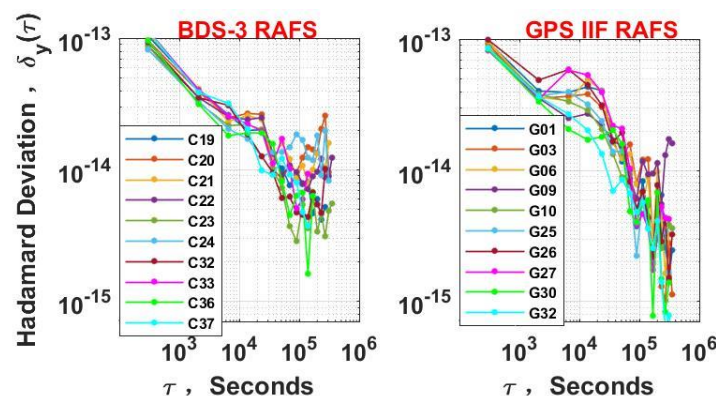
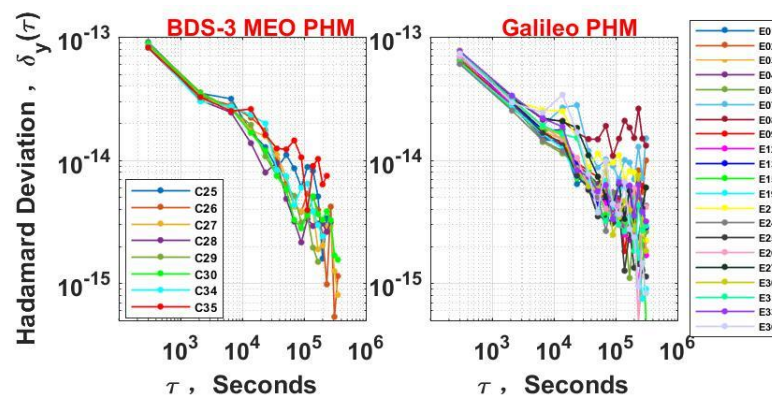


Figure 14. HDEV of the differenced frequency data for BDS-3 MEO RAFS and GPS IIF RAFS satellites with respect to KOUR station.





**Figure 15.** HDEV of the differenced frequency data for BDS-3 MEO PHM and Galileo PHM satellites with respect to KOUR station.

The volume and weight of BDS-3 RAFS clocks are smaller than those of BDS-2. Besides, the very-high precision spaceborne RAFS was first carried on C36 and C37 satellites, which is the key for providing decimeter-magnitude positioning accuracy. From the results, it can be seen that the clock performance of the two satellites is basically comparable to other BDS-3 RAFS satellites, in spite of the 10,000 s and 1 d stability being slightly better. It should be noted that the number of visible stations (used in POD of XRS product) for C35, C36, and C37 satellites, with about a dozen stations, is fewer than other BDS-3 satellites with at least 30 visible stations. This may be also the reason that the clock STD of the three satellites between XRS and WUM products is bigger than other BDS-3 satellites. The clock performance between BDS-3 RAFS and GPS IIF RAFS has respective advantages in different aspects. The 10,000 s stability of BDS-3 RAFS is better than GPS, but for other indexes, the clock performance of GPS is superior.

More importantly, for the first time, there are eight BDS-3 satellites carrying PHM in the construction of BDS. Compared to RAFS, the key technical indexes (i.e., the frequency accuracy, drift rate, and stability) are superior, which has a significant influence on users' positioning and timing accuracy, prediction performance, and autonomous navigation. The PHM includes a physical and electronics package and the working mechanism is different from RAFS. The specific work procedure can be found in [20]. The above results show the excellent performance of the PHM clock in terms of the three indexes, especially the frequency drift rate of PHM, which is basically two orders of magnitude smaller than RAFS satellites. On the whole, the clock performance of BDS-3 PHM is comparable to Galileo satellites, except C34 and C35 have large drift rates and the 10,000 s stability of BDS-3 is slightly worse than Galileo satellites.

Generally, when processing the stability analysis in the time domain, the reference frequency standard should be one-third smaller than that of the tested atomic clocks. The stability of 10,000 s and 86,400 s is  $8.93 \times 10^{-15}$  and  $1.85 \times 10^{-15}$ , respectively, for the differenced values between receiver clocks of MGUE and KOUR with both attached to high-precision AHM. The threefold value of  $8.93 \times 10^{-15}$  is  $2.68 \times 10^{-14}$ , which is basically comparable to the 10,000 s stability of BDS-3 PHM with the value  $2.32 \times 10^{-14}$ . The threefold value of  $1.85 \times 10^{-15}$  is  $5.55 \times 10^{-14}$ , which is basically comparable to the 10,000 s stability of BDS-3 PHM with the value  $5.28 \times 10^{-14}$ . Therefore, the stability results at the averaging time of 10,000 s and 86,400 s are basically convincing.

## 6. Conclusions

This study assesses the clock performance for the BDS-3 basic system with 18 MEO satellites (8 with PHM and 10 with RAFS), in terms of frequency accuracy, daily drift rate, and stability at the averaging time of 300 s, 10,000 s, and 1 day. First orbits and clocks of XRS products are compared to WUM and IGS final products. The GPS result shows the accuracy of orbits and clocks is comparable to the WUM products. The BDS orbits comparison result of XRS products with respect to WUM products



is in the order of decimeter magnitude and the clock STD is about 0.2 ns, which are worse than the results of GPS and Galileo satellites. We give the possible reason.

Then, we develop a data auto-editing procedure to preprocess clock data and assess the clock performance at each continuous arc. With the outliers excluded and day boundary problem solved using the specific strategy, the clean frequency data can be derived. The ODTs noise is derived by four stations attached to high-precision AHM. The average values of 10,000 s and 86,400 s stability are  $1.13 \times 10^{-14}$  and  $2.68 \times 10^{-15}$ , respectively, where the best results are between MGUE and KOUR stations with the values being  $8.93 \times 10^{-15}$  and  $1.85 \times 10^{-15}$ , respectively. These results indicate that the level of ODTs noise can be basically neglected when processing the performance assessment of GNSS clocks.

BDS-3 clock performance is compared with that of GPS BLOCK IIF RAFS, Galileo PHM, and BDS-2 RAFS satellites. In terms of frequency accuracy, the average values of BDS-3 RAFS and PHM are  $2.29 \times 10^{-11}$  and  $1.48 \times 10^{-11}$ , respectively, where the RAFS is comparable to BDS-2, and the PHM is comparable to GPS with the value of  $9.30 \times 10^{-12}$  and Galileo with the value of  $9.37 \times 10^{-12}$ . As for the frequency daily drift rate, the average value of BDS-3 RAFS is  $1.48 \times 10^{-13}$ , which is slightly worse than BDS-2 MEO satellites with the value of  $9.04 \times 10^{-14}$ . The mean value of BDS-3 PHM is  $1.44 \times 10^{-15}$  except C34 and C35, which is significantly better than the  $2.22 \times 10^{-14}$  of GPS and basically comparable to the  $1.25 \times 10^{-15}$  of Galileo. In terms of the stability at 300 s averaging time, the BDS-3 RAFS value is  $9.43 \times 10^{-14}$ , which is better than BDS-2 satellites. The BDS-3 PHM value is  $9.07 \times 10^{-14}$ , which is slightly better than the GPS value of  $8.91 \times 10^{-14}$  and slightly worse than the Galileo value of  $7.08 \times 10^{-14}$ . The stability at 300 s averaging time among GPS IIF RAFS, Galileo PHM, and BDS-3 satellites is basically comparable. The 10,000 s stability of BDS-3 RAFS is  $2.49 \times 10^{-14}$ , which is better than BDS-2 and GPS satellites. The BDS-3 PHM value is  $2.32 \times 10^{-14}$ , which is better than the GPS value of  $4.14 \times 10^{-14}$  and slightly worse than the Galileo value of  $1.77 \times 10^{-14}$ . As for the stability of 86,400 s, the BDS-3 RAFS is  $8.64 \times 10^{-15}$ , which is better than BDS-2 satellites. The BDS-3 PHM is  $5.28 \times 10^{-15}$ , which is slightly worse than the GPS value of  $4.52 \times 10^{-15}$  and better than the Galileo value of  $5.57 \times 10^{-15}$ . Therefore, the clock performance of BDS-3 PHM is basically comparable to Galileo satellites and that of BDS-3 RAFS is better than BDS-2.

**Author Contributions:** X.J. proposed the initial idea of this study and supervised the experiments. T.Z. performed the experiments and wrote the paper. R.R. provided the XRS products. X.J., Y.M., and G.X. reviewed the paper.

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