# Analysis of BDS Satellite Clock in Orbit with ODTS and TWTT Satellite Clock Data

**Bin Wang and Junping Chen**

**Abstract** Two Way Time Transfer (TWTT) is used in BDS to synchronize the time between satellite and ground system. Therefore, both Orbit Determination and Time Synchronization (ODTS) and TWTT can obtain BDS satellite clocks. For ODTS, satellite clock is estimated with satellite orbit, and the consistency of them is better, but estimation error of them cannot be separated. Compared with ODTS, satellite clock estimated by TWTT is less impacted by satellite orbit, because of the difference between uplink and downlink pseudo-ranges in TWTT processing. Consistency of ODTS satellite clock and TWTT satellite clock is of importance for the performance analysis of BDS satellite clock in orbit. Based on the satellite clocks estimated by ODTS and TWTT respectively, this paper analyzes the systematic, periodical and stochastic characteristics of BDS satellite clock, taking into account the characteristics of satellite clock data. The result can provide reference for BDS service performance optimization. It is shown that the performance of BDS satellite clock is approximately $5 \times 10^{-12}\ \tau^{-0.5}$ (WHFM, $10^3$ s $\tau \leq 10^4$ s) + $4 \times 10^{-14}$ (FLFM, $\tau > 10^5$ s), while during the $10^4$–$10^5$ s period, the orbital-period characteristics is notable.

**Keywords** Beidou navigation satellite system · Orbit determination and time synchronization · Two way time transfer · Satellite clock in orbit
Noise analysis

---

B. Wang · J. Chen (✉)
Shanghai Astronomical Observatory, Chinese Academy of Sciences,
Shanghai 200030, China
e-mail: junping@shao.ac.cn

J. Chen
School of Astronomy and Space Science, University of Chinses
Academy of Sciences, Beijing 100049, China

J. Sun et al. (eds.), *China Satellite Navigation Conference (CSNC) 2018 Proceedings*, Lecture Notes in Electrical Engineering 497,
https://doi.org/10.1007/978-981-13-0005-9_50

# 1 Introduction

Performance of GNSS is closely related to that of on board atomic clock. Navigation, positioning and timing accuracy is affected by the performance of satellite clock, through the influences of satellite clock modeling and forecasting. Different from the other GNSSs (such as GPS, GLONASS and Galileo) using the orbit determination and time synchronization (ODTS) technique for the time synchronization between satellites and ground system, two-way time transfer (TWTT) is used by BDS [1]. In ODTS algorithm, ionosphere-free linear combinations of L1 and L2 phase and code observations are taken as input. Through the separation of various propagation delays (such as tropospheric delay), estimations of satellite orbit and satellite clock are obtained [2]. Up-link and down-link pseudo-ranges between satellite and ground station is used by TWTT to perform the time comparison between satellite and the station, and only the satellite clock is estimated.

Through the differences between up and down-link pseudo-ranges, TWTT can eliminate the influences of some common errors, such as the tropospheric delay, satellite ephemeris errors and so on, to the satellite clock estimations [3]. Compared with satellite clock estimation obtained by ODTS algorithm, TWTT satellite clock estimation is relatively less affected by the satellite orbit, however ODTS satellite clock is more consistent with the ODTS satellite orbit. Code pseudo-range and carrier phase observations are generally processed by ODTS algorithm. Absolute reference of satellite clock is provided by the pseudo-range, while the precision of satellite clock estimation is usually determined by the precision of carrier phase observations. Precision of ODTS satellite clock is around 33 ps [4], while the precision of TWTT satellite clock is affected by the precision of code pseudo-range. Therefore, ODTS satellite clock and TWTT satellite clock have different but complementary attributes. They can be used to reveal different aspects of BDS satellite clock performance. Comparative analysis of ODTS and TWTT 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.

Analysis of BDS satellite clock is of great significance for understanding the status of BDS service and discussing the improvement of BDS service performance. At present, many scholars have carried out a large number of work of performance analysis of BDS satellite clocks based on ODTS clock data [5–8]. However, performance analysis of BDS satellite clock based on TWTT clock data is rarely carried out, and comparative analysis of BDS satellite clock performance result based on these two kinds of different clock data has not been carried out yet. In this paper, we compare TWTT and ODTS satellite clock data of BDS, and analyze their performance. The analysis is carried out from three aspects: characteristics of satellite clock data, characteristics of the periodic variation of satellite clock, and random characteristics of satellite clock.

## 2 Comparison of Satellite Clock Data

### 2.1 *Mutual Agreements of ODTS and TWTT Satellite Clock Data*

Due to different observations, processing algorithms and software implementations used by ODTS and TWTT algorithms, satellite clock data obtained by these two algorithms can be regarded as independent from each other, and therefore the mutual agreements of them can be obtained by comparative analysis of these two kinds of satellite clock data.

After removing the influences of different time reference, mutual agreements between TWTT and ODTS satellite data is shown in Fig. 1. Figure 1 shows the time variations of the difference between ODTS and TWTT satellite clock data from September 18 to September 21, 2013 and the functional relationship between the difference and the satellite orbit angle μ. It is can be seen that there is some correlation between the difference of these two kinds of satellite clock data and satellite orbit. Amplitudes of 1 cpr (cycle per revolution) for C01 and C05 satellites are 1 ns and 0.6 ns respectively, while those of C06 and C09 satellites are 0.4 and 0.3 ns, respectively.

In TWTT algorithm, differences of up-link and down-link code pseudo-range are used to estimate the satellite clock, thus the orbit error has little effect on the satellite clock estimates. ODTS algorithm estimates both satellite orbit and satellite clock, and satellite clock estimates would be affected by satellite orbit estimation error. Under the assumption that TWTT satellite clock data is relatively less affected by the orbit estimation error, the above phenomenon indicates that there is an influence of the satellite orbit estimation error in the ODTS satellite clock data.

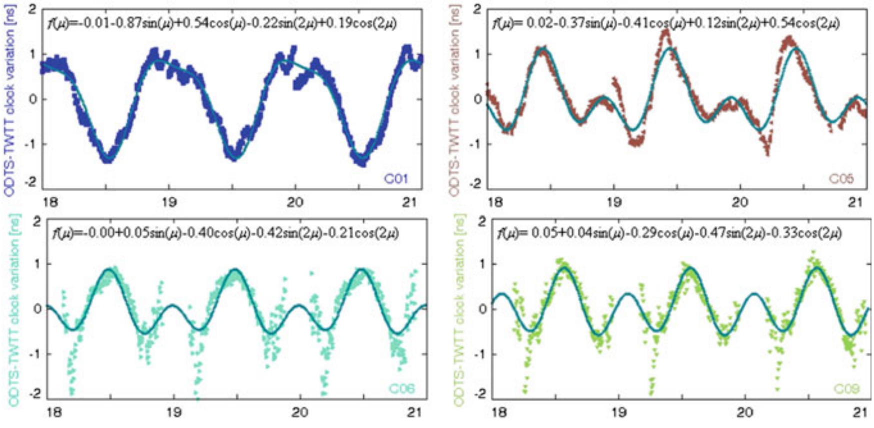

**Fig. 1** Periodicity of difference between ODTS and TWTT clock

## 2.2 *Internal Consistency Comparison of OTDS and TWTT Satellite Clock Data*

The internal consistency was evaluated by the 95.5 quantile of the RMS error for quadratic polynomial fitting of daily satellite clock data, and the results are shown in Table 1. It can be seen that for GEO satellites, the internal consistency of TWTT satellite clock data is better than that of ODTS satellite clock data, while for IGSO satellites, the internal consistency of them is comparable.

# 3 Comparison of Periodicity Analysis Results Based on ODTS and TWTT Satellite Clock Data

Periodicity analysis results based on ODTS and TWTT satellite clock data are compared from two aspects: period, amplitude. Analysis results using ODTS satellite clock data can be referred to relevant literature, such as [9].

Analysis results based on the TWTT satellite clock are shown in Fig. 2. It can be seen that 12 h (2 cpr) harmonics of GEO and IGSO satellites clock is noticeable, and IGSO satellite clock has the n cpr harmonics. The amplitude of harmonics decreases with the increase of n. Compared with the analysis results based on ODTS satellite clock, the amplitude of 24 h (1cpr) harmonic of GEO and IGSO satellites using TWTT satellite clock data is smaller.

In summary, periodic variation characteristics of n (n is a positive integer) cpr for the BDS satellite clock can be obtained whether using ODTS satellite clock data or TWTT satellite clock data. Results of harmonic period of BDS satellite clock analyzed by these two kinds of satellite clock data are consistent with each other, while there are some differences in the amplitudes. Amplitude results analyzed by TWTT satellite clock data is smaller than the results analyzed by the ODTS satellite clock data, especially for the 1 cpr harmonic.

**Table 1** Internal consistency comparison of ODTS and TWTT clock (second half of the year 2013)

| Orbit/PRN | | Type | |
|---|---|---|---|
| | | ODTS [s] | TWTT [s] |
| GEO | C01 | 9.72E−10 | 6.71E−10 |
| | C02 | 4.52E−09 | 3.91E−09 |
| | C03 | 1.10E−09 | 6.28E−10 |
| | C04 | 1.73E−09 | 1.63E−09 |
| | C05 | 1.23E−09 | 8.61E−10 |
| IGSO | C06 | 1.87E−09 | 1.49E−09 |
| | C07 | 8.33E−10 | 6.87E−10 |
| | C08 | 4.83E−10 | 5.72E−10 |
| | C09 | 6.57E−10 | 7.81E−10 |
| | C10 | 9.19E−10 | 7.18E−10 |

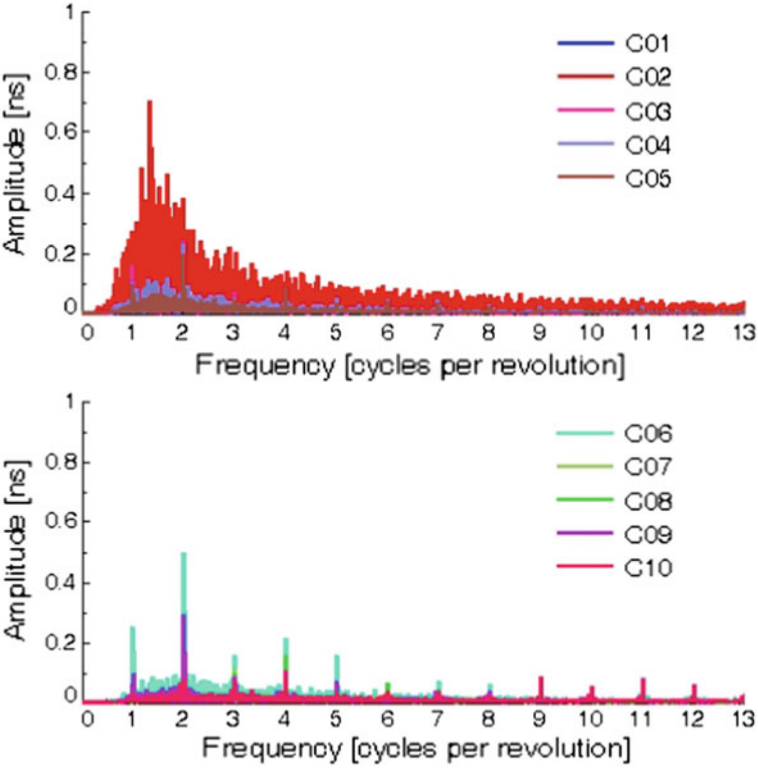

**Fig. 2** Periodogram of BDS satellite clock based on TWTT satellite clock data

## 4 Comparison of Stability Analysis Results Based on ODTS and TWTT Satellite Clock Data

Stability analysis results based on ODTS and TWTT satellite clock data are compared from three aspects: time domain variances of frequency stability, dominant power law noise type and power law spectral densities. Analysis results of C05 (GEO) satellite and C07 (IGSO) satellite clock are described. Allan, Hadamard and Modified Allan deviation calculated by these two kinds of clock data are respectively compared, and the noise types in different time periods are analyzed. Among these methods, the Hadamard deviation is insensitivity to linear frequency drift, and comparison of Hadamard deviation and Allan deviation is useful to validate the frequency stability analysis algorithm; modified Allan deviation is used to distinguish between white and flicker PM noise.

Stability analysis results of C05 satellite clock are shown in Fig. 3. It can be seen that variances calculated using TWTT satellite clock data is larger than that calculated using ODTS satellite clock data in the period of $3 \times 10^2$–$5 \times 10^4$ s, while

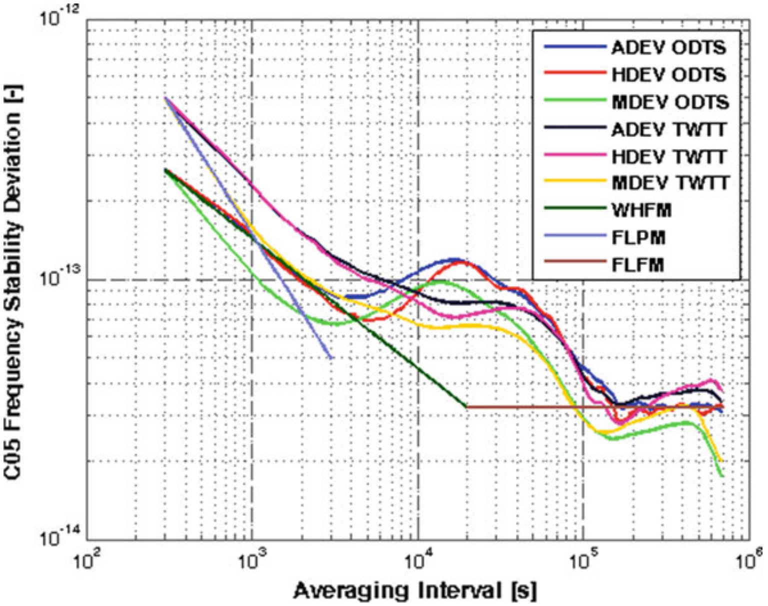

**Fig. 3** Result comparison of frequency stability analysis for C05 satellite clock based on TWTT and ODTS satellite clock data. Allan deviation denoted by ADEV, Hadamard deviation denoted by HDEV, and modified Allan deviation denoted by MDEV

the variances calculated by both satellite clock data in the period of larger than $5 \times 10^4$ s are consistent with each other.

For TWTT satellite clock data, remarkable effect of flicker phase modulation (FLPM) noise can be seen in the period of $3 \times 10^2$–$1 \times 10^3$ s. While in the period of $1 \times 10^3$–$1 \times 10^4$ s, power law noise type analyzed from TWTT satellite clock data is white frequency modulation (WHFM) noise, which is the same as that analyzed using ODTS satellite clock data. TWTT satellite clock data is affected by the periodic variations of satellite orbit during the period of $10^4$ s to one orbit period (satellite orbit period of GEO and IGSO satellites is one day). However, the periodic variations influences on TWTT are much smaller than of ODTS. In the period of longer than one satellite orbit period, power law noise type obtained using both satellite clock data is the same, and both are the flicker frequency modulation (FLFM) noise.

Frequency stability analysis results of C07 satellite clock are shown in Fig. 4. Comparison results of frequency stability analysis using both satellite clock data is consistent with that of C05 satellite clock.

Power law spectral densities analyzed from ODTS and TWTT satellite clock data are the same, except for the FLPM noise in the short period. It is inferred that performance parameters of BDS satellite clock in orbit is $5 \times 10^{-12}\ \tau^{-0.5}$ (WHFM, $10^3\ \text{s} \leq \tau \leq 10^4\ \text{s}$) + $4 \times 10^{-14}$ (FLFM, $\tau > 10^5$ s).

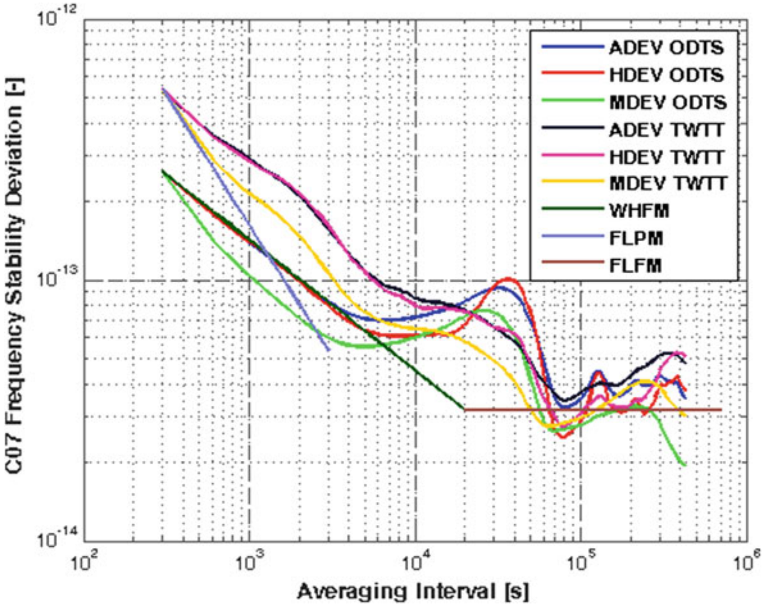

**Fig. 4** Result comparison of frequency stability analysis for C07 satellite clock based on TWTT and ODTS satellite clock data. Allan deviation denoted by ADEV, Hadamard deviation denoted by HDEV, and modified Allan deviation denoted by MDEV

## 5 Conclusions

Analysis of BDS satellite clock based on ODTS and TWTT satellite clock data shows that, (1) for GEO satellites, the internal consistency of TWTT satellite clock data is better than that of ODTS satellite clock data, while for IGSO satellites, the internal consistency of both satellite clock data is comparable. (2) 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, especially for the one cpr harmonic. (3) Difference between ODTS and TWTT satellite clock data has relationship with the satellite orbit angle, this phenomenon indicates that one cpr periodic variation of ODTS satellite clock data is related to the satellite orbit estimation error, especially for GEO satellites. (4) Comparative analysis of frequency stability analysis results obtained from ODTS and TWTT satellite clock data shows that, in the period of $10^2$–$10^3$ s, remarkable effect of FLPM noise on the analysis results of TWTT satellite clock data can be seen. Power law spectral densities analyzed from ODTS and TWTT satellite clock data are almost the same. It is inferred that performance parameters of BDS satellite clock in orbit is $5 \times 10^{-12}\,\tau^{-0.5}$ (WHFM, $10^3$ s $\leq \tau \leq 10^4$ s) + $4 \times 10^{-14}$ (FLFM, $\tau > 10^5$ s).

**Acknowledgements** This work is support by the NSFC (No.11673050), the 863 (No. 2014AA123102) projects and also the open project program of the key lab of space navigation and positioning technology (No. KFKT-201705), Shanghai.

## References

1. Han C, Cai Z, Lin Y (2013) Time synchronization and performance of Beidou satellite clocks in orbit. Int J Navig Obs 2013:5
2. Zhao Q, J Guo, M Li (2013) Initial results of precise orbit and clock determination for compass navigation satellite system. J Geod 87(5):475–486
3. Liu L, Zhu L, Han C (2009) The model of radio two-way time comparison between satellite and station and experimental analysis. Chin Astron Astrophys 33(4):431–439
4. Senior KL, Ray JR, Beard RL (2008) Characterization of periodic variations in the GPS satellite clocks. GPS Solut 12(3):211–225
5. Gong H, Ni S, Mou W, et al (2012) Estimation of compass on-board clock short-term stability. In: Proceeding of the 26th European frequency and time forum (EFTF), Gothenburg, Sweden
6. Zhou P, Du L, Zhang Z, et al (2014) Preliminary performance evaluation of Beidou spaceborne atomic clocks. In: Proceedings of China satellite navigation conference (CSNC) 2014. Springer, Berlin, Heidelberg
7. Montenbruck O, Steingenbrger P, Hugentobler U, et al (2013) Initial assessment of the Compass/Beidou-2 regional navigation satellite system. GPS Solut 17(2): 211–222
8. Steigenberger P, Hugentobler U, Hauschild A, et al (2013) Orbit and clock analysis of compass GEO and IGSO satellites. J Geod 87(6):515–525
9. Wang B, Lou Y, Liu J, et al (2016) Analysis of BDS satellite clocks in orbit. GPS Solut 20 (4):783–794