Research Article

Time Synchronization and Performance of BeiDou Satellite Clocks in Orbit

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The time model of BeiDou satellite clocks is analyzed. The general relations of satellite clocks with the system time are studied. The error sources of two-way radio time transfer between satellites and uplink stations are analyzed. The uncertainty of type A is about 0.3 ns in BeiDou system. All the satellite clocks in orbit of BeiDou satellite navigation system are evaluated by the clock offsets observed by the two-way radio time transfer. The frequency stabilities at a sample time of 10000 s and 1 day for all the satellite clocks are better than 1.0×10^{-13} . It means that the performance of BeiDou satellite clocks in orbit is consistent with the ground test, and the results in orbit are a little better than those in ground vacuum.

1. Introduction

BeiDou satellite navigation system began to provide regional service since December 2012. The constellation of BeiDou system is constituted of 14 satellites in orbit: 5 GEO satellites, 5 IGSO satellites, and 4 MEO satellites. Table 1 shows the basic information of the BeiDou satellites. Service area now covers latitude $55^{\circ}\text{S} \sim 55^{\circ}\text{N}$ and longitude $55^{\circ}\text{E} \sim 180^{\circ}\text{E}$. Practical operational accuracy of BeiDou system is better than 10 m (95%) in horizontal and 15 m (95%) in vertical [1].

As we all know that time synchronization of satellite clock plays a significant role in satellite navigations, accurate and reliable satellite clock offset parameters are the base of PNT service. Time synchronization error of satellite clock is mainly caused by the time transfer from the master station and its offset prediction. The clock prediction error depends on its frequency instability. Then the measurement, prediction and evaluation, of satellite clocks are very important for a satellite navigation system.

GPS operates a worldwide monitoring stations network, and includes six USAF stations, eleven NGA stations, and two IGS stations. Geodetic receivers are equipped in these stations to monitor the performance of satellite clocks. On 28 May, 2010, the first Block IIF satellite, designated SVN62/PRN25, was launched containing three atomic frequency standards,

one DCBFS serial number 1010 (Cs 1010) and two RFS serial numbers 27 and 14 (Rb 27 and Rb 14). The frequency stabilities of SVN62 Cs 1010 and Rb 27 are, respectively, 5×10^{-14} and 7×10^{-15} at 1 day in orbit. And the frequency stability of GPS Block IIR Rb is about 9×10^{-15} at 1 day for October 2010 (all using NGA data) [2–4] while the frequency stability at 1 day for Galileo satellite clock is about 5×10^{-14} for GIOVE A Rb clocks and 8×10^{-15} for GIOVE B PHM [5, 6].

How about the performance of BeiDou clocks in orbits? It is a very concerned question for many GNSS users. The system signals and observations of BeiDou regional system are analyzed by Deutsches Zentrum für Luft- und Raumfahrt (DLR) using a local monitoring network in March 2012. The short-term stability and middle-term stability of BeiDou satellite clocks are analyzed and compared to other systems. Frequency stability of BeiDou RAFS is about $7 \times 10^{-12} \sim 1 \times 10^{-11}$ at 1 second, Frequency stability of the best BeiDou satellite clock is about 1×10^{-13} at 1000 seconds, and GPS Block IIF is not worse than 1×10^{-13} [7]. In the following sections, the time model of satellite clocks used by BeiDou system is described; then the error source and uncertainty of the two-way radio time transfer (TWTT) are analyzed, which is used to measure clock differences between satellites and the uplink stations. Finally, the results and conclusions are detailed.

TABLE 1: Basic information of Beidou satellite clocks.

Num	Type (Num)	Date
03	GEO-1	2010.1.17
04	GEO-3	2010.6.2
05	IGSO-1	2010.8.1
06	GEO-4	2010.11.1
07	IGSO-2	2010.12.18
08	IGSO-3	2011.4.10
09	IGSO-4	2011.7.27
10	IGSO-5	2011.12.2
11	GEO-5	2012.2.25
12	MEO-3	2012.4.30
13	MEO-4	2012.4.30
14	MEO-5	2012.9.19
15	MEO-6	2012.9.19
16	GEO-6	2012.10.25

2. Time Model of Satellite Clocks

Considering the large-scale spacetime involved (about 1×10^5 km in space and several days, even several months or years in time) and the precision requirements (1 m, even 1 cm, 1 mm level), the GNSS data process must be dealt with under the framework of relativity and quantum theory. Two kinds of conceptually different time scales are concerned in GNSS, proper times, and coordinate times. Essentially, for any two events, the observed space interval and time interval between them are dependent on the observer. The time readings given directly by ideal clocks located in satellites, stations, or observers are proper times. They are related to the observer, or to the spacetime environments of the clocks. This means that different observer has different clock due to its relative velocity and position in the gravitation field. In order to have a common time reference for all observers, we must choose a special observer and construct a reference system. A reference system contains a 3-dimensional space reference frame and a time reference. The former determines the spatial position (3 space coordinates) of an event and the latter gives the happening time, which is called coordinate time. For Earth satellites, a nonrotating geocentric reference system is used to describe their orbits. The reference time is usually TCG (the geocentric coordinate time) or TT (the terrestrial time) [8, 9].

The relationship between the proper time τ of satellite and the coordinate time TT (here noted by t) can be modeled as [8]

$$t = \left[1 - \frac{W_0 - (3/2)(\mu/a)}{c^2} \right] (\tau - \tau_0) + \frac{2}{c^2} \sqrt{\mu a} \cdot e (\sin E - \sin E_0), \quad (1)$$

where $\mu = GM_E$ is the geocentric gravitation constant, W_0 the gravity potential of the geoid, a the orbit main axis, e

the eccentricity, E the real eccentric anomaly, and c the speed of light, respectively. Then,

$$\tau - t = \left[\frac{W_0 - ((3/2)(GM_E/a))}{c^2} \right] (t - t_0) - \frac{2}{c^2} \sqrt{aGM_E} \cdot e \sin E \quad (2)$$

If the satellite clock $T(t)$ is modeled as

$$T(t) = \tau(t) + a_0 + a_1(t - t_0) + a_2(t - t_0)^2 + \xi(t). \quad (3)$$

in which a_0 , a_1 , and a_2 are clock offset parameters and $\xi(t)$ is the clock phase noise, the offset of satellite clock referred to BDT can be written as

$$x(t) \equiv T(t) - \text{BDT}(t) = a_0 + a_1(t - t_0) + a_2(t - t_0)^2 + \Delta t_{\text{grav}}^p + \xi(t) \quad (4)$$

Here Δt_{grav}^p is the periodic term of relativistic effect as follows:

$$\Delta t_{\text{grav}}^p = -\frac{2}{c^2} \sqrt{\mu a} e \sin E = -\frac{2\vec{x}_S \cdot \dot{\vec{x}}_S}{c^2}. \quad (5)$$

The relativistic effect must be taken into account for the evaluation of clock performance. If not, the stability of frequency will be influenced. The quasi-half-day periodical terms in Allan deviations of GPS clocks and Galileo clocks [2, 5], we guess, may be caused by this term.

3. Two-Way Satellite Time Transfer and Error Analysis

In Beidou system, TWTT between satellites and uplink stations is used for the satellitetime synchronization. The basic principle of TWTT is as follows. The satellites and stations generate and transmit pseudo-range signals controlled by their local clocks; then the uplink pseudo-range ρ_u and downlink pseudo-range ρ_d are measured by the satellites and the stations, respectively. The uplink pseudo-range and downlink pseudo-range can be written as

$$\begin{aligned} \rho_u(T_S^r) &= |\vec{x}_S(t_S^r) - \vec{x}_R(t_R^e)| \cdot \frac{1}{c} - \Delta T_R(t_R^e) + \Delta T_S(t_S^r) \\ &\quad + \tau_R^e + \tau_S^r + \tau_{\text{tro}} + \tau_{\text{ion}}(f_u) + \tau_{\text{grav}}, \\ \rho_d(T_R^r) &= |\vec{x}_R(t_R^r) - \vec{x}_S(t_S^e)| \cdot \frac{1}{c} + \Delta T_R(t_R^r) - \Delta T_S(t_S^e) \\ &\quad + \tau_R^r + \tau_S^e + \tau_{\text{tro}} + \tau_{\text{ion}}(f_d) + \tau_{\text{grav}}, \end{aligned} \quad (6)$$

where t_S^r and t_S^e are time of reception and emission of the satellite signal; t_R^r and t_R^e are time of reception and emission of the station signal; ΔT_S and ΔT_R are satellite and station's clock offset; τ_R^r and τ_R^e are time delay of reception and emission of the station equipment; τ_S^e and τ_S^r are time delay of reception and emission of the satellite equipment; τ_{tro} and τ_{ion} are

troposphere delay and ionosphere delay; f_u and f_d are uplink frequency and downlink frequency; τ_{grav} relativistic time delay caused by Earth gravitation.

The clock differences between satellites and stations are computed in the master station by using the uplink pseudo-ranges and the downlink pseudo-ranges. The satellite clock offset can be given by the observed uplink pseudo-range and downlink pseudo-range as follows:

$$\begin{aligned} \Delta T_S(t^i) = & \Delta T_R(t^i) + \frac{1}{2} \\ & \times \{ [\rho_u(T_S^i) - \rho_d(T_R^i)] \\ & - \frac{1}{c} (\dot{\vec{x}}_S - \dot{\vec{x}}_R) \cdot \vec{n}_{RS} (\Delta T_S - \Delta T_R - \tau_{RS}) \\ & + \Delta \tau_R - \Delta \tau_S - \Delta \tau_{\text{ion}} \} + \dots, \end{aligned} \quad (7)$$

where

$$\begin{aligned} \Delta \tau_R &\equiv \tau_R^r - \tau_R^e, \\ \Delta \tau_S &\equiv \tau_S^r - \tau_S^e, \\ \Delta \tau_{\text{ion}} &\equiv \tau_{\text{ion}}(f_u) - \tau_{\text{ion}}(f_d), \\ \vec{n}_{RS} &\equiv \frac{(\vec{x}_S - \vec{x}_R)}{|\vec{x}_S - \vec{x}_R|}. \end{aligned} \quad (8)$$

The random error of satellite clock difference includes the noise of pseudo-range observable and the satellite clock phase noise. In short term (≤ 1000 s), the influence of the frequency drift and phase noise of satellite clock to clock offset can be neglected. So the uncertainty of type A of satellite-board clock offset measurement can be calculated by the fluctuation of clock difference. Analysis shows that the uncertainty of type A is less than 0.3 ns [10]. In middle or long term (≥ 10000 s), the influence of the pseudo-range noise can be neglected, and the results of the Allan variance of satellite clocks are reliable.

4. Performance Evaluation of Beidou Satellite Clocks in Orbit

Satellites that include GEO satellites of serial number 03, 04, 06, and 11, IGSO satellites of serial number 07, 08, 09 and 10, and MEO satellites of serial number 13 and 14 are evaluated. In order to ensure the reliability of the evaluation result, the time interval of satellite clock data is no less than 15 days. The time scale reference for analysis is the high performance hydrogen clock in ground.

Figures 1, 2, and 3 show the linear residuals and second-order polynomial residuals of the observed satellite clock offsets.

The green curves are plots of the linear residuals of satellite clocks. All of the linear residual of GEO-3, GEO-4, and IGSO-2 are smooth, which mean that the rubidium clocks have significant frequency drifts. The blue curves are the second-order polynomial residuals of satellite clocks, which

FIGURE 1: Residual of GEO-3 satellite clock.

FIGURE 2: Residual of GEO-4 satellite clock.

FIGURE 3: Residual of IGSO-2 satellite clock.

TABLE 2: Frequency stability of Beidou system satellite clocks.

	GEO-1	GEO-3	GEO-4	GEO-5	IGSO-1	IGSO-2	IGSO-3	IGSO-4	IGSO-5
Stability (10000 s)	7.31×10^{-14}	5.52×10^{-14}	7.58×10^{-14}	9.17×10^{-14}	8.13×10^{-14}	5.95×10^{-14}	7.94×10^{-14}	8.53×10^{-14}	8.98×10^{-14}
Stability (1 day)	6.71×10^{-14}	2.90×10^{-14}	3.83×10^{-14}	5.66×10^{-14}	9.38×10^{-14}	3.07×10^{-14}	2.53×10^{-14}	3.91×10^{-14}	4.45×10^{-14}

FIGURE 4: Frequency stability of Beidou system satellite clocks.

demonstrate that the frequency drifts are changing slowly and the rubidium clocks in orbit have high-level noise characteristic, such as flick and random walk.

The frequency stability of Beidou satellite clocks is evaluated by use of the overlapping Allan deviation. Figure 4 shows plots of the frequency stability of Beidou system satellite clocks. Table 2 shows the frequency stability at a sample time of 10000 seconds and 1 day.

The frequency stability of Beidou satellite clocks is of the level of 10^{-14} at a sample time of 10000 seconds and 1 day. The frequency stability at a sample time of 10000 seconds is about $5.95 \sim 9.17 \times 10^{-14}$, and that at a sample time of 1 day is about $2.53 \sim 9.38 \times 10^{-14}$.

Figure 5 gives the comparison of the clock performances in orbit and in the ground vacuum. The results show that the performances in orbits are conformable with those in ground. As a whole, the results in orbit are a little better than those in ground.

5. Conclusion

The long-term evaluation for Beidou satellite clocks has been done using TWTT between satellites and stations. The results

FIGURE 5: Clock day stabilities in orbit and in ground vacuum pots.

show that the performance of satellite clock is steady and in good condition. The frequency stabilities at a sample time of 10000 s and 1 day for all the satellite clocks are better than 1.0×10^{-13} . It means that the performance of Beidou satellite clocks in orbit is consistent with the ground test, and the results in orbit are a little better than those in ground vacuum.

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