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BeiDou Navigation Satellite System and its time scales

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Abstract
The development and current status of BeiDou Navigation Satellite System are briefly introduced. The definition and realization of the system time scales are described in detail. The BeiDou system time (BDT) is an internal and continuous time scale without leap seconds. It is maintained by the time and frequency system of the master station. The frequency accuracy of BDT is superior to $2 \times 10^{-14}$ and its stability is better than $6 \times 10^{-15}/30$ days. The satellite synchronization is realized by a two-way time transfer between the uplink stations and the satellite. The measurement uncertainty of satellite clock offsets is less than 2 ns. The BeiDou System has three modes of time services: radio determination satellite service (RDSS) one-way, RDSS two-way and radio navigation satellite service (RNSS) one-way. The uncertainty of the one-way time service is designed to be less than 50 ns, and that of the two-way time service is less than 10 ns. Finally, some coordinate tactics of UTC from the viewpoint of global navigation satellite systems (GNSS) are discussed. It would be helpful to stop the leap second, from our viewpoint, but to keep the UTC name, the continuity and the coordinate function unchanged.

1. Introduction

As an important space information infrastructure BeiDou Navigation Satellite System has been paid considerable attention by the Chinese government. Analogous to other global navigation satellite systems (GNSS), this system also has three segments: the space segment, the control segment and the user segment. Its final goal is to provide global, accurate and reliable position–navigation–time (PNT) services and short-message services for users anywhere in the world irrespective of the time and weather.

The development of the system is divided into two steps [1, 2]: the BeiDou Navigation Demonstration System and the BeiDou Navigation Satellite System, and programmed in three phases. Phase I, from 2000 to 2012, is called the BeiDou Demonstration Navigation System which provides the radio determination satellite service (RDSS) and the short-message services for users in China and the surrounding area. The satellite constellation consists of three geostationary (GEO) satellites located at 80°E, 110.5°E, 140°E, respectively. From 2012 to 2020 is phase II: the radio navigation satellite service (RNSS) will be increased from the basis of BeiDou Demonstration System to possess regional navigation ability. The satellite constellation consists of five GEO satellites (58.75°E, 80°E, 110.5°E, 140°E, 160°E), five inclined geosynchronous orbit (IGSO) satellites in two orbits with 55° orbit inclinations, and 118°E and 98°E ascending nodes, respectively, referred to as the Earth-fixed reference system, and four medium Earth orbit (MEO) satellites, which have 27 878 km semi-major axis and 55° orbit inclinations. The current status of the system will be given briefly in section 2.

In phase III, the MEO satellites may be increased to 27 and work in the Walker 24/3/1 constellation. The positioning accuracy will be superior to 10 m and the timing accuracy to 20 ns. The roadmap is shown in figure 1.

It is well known that time scales play very important roles in a navigation system. In section 3 we will give some more details about the time scales and time synchronization of the BeiDou Navigation Satellite System. In section 4, the coordinated characteristics of UTC are discussed from the viewpoint of GNSS. Section 5 gives a brief conclusion.

2. Current status of the BeiDou System

At present, the research and development phase of BeiDou Regional Navigation Satellite System is occurring [3, 4]. Up
Figure 1. Roadmap of the BeiDou Navigation System.

Table 1. The launch missions of BeiDou satellites up to 03/2011.

<table>
<thead>
<tr>
<th>Date</th>
<th>Type</th>
<th>Launch centre</th>
<th>Launch carrier</th>
<th>Launch cabin</th>
<th>Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007.04.14</td>
<td>MEO</td>
<td>Xichang</td>
<td>CZ-3A</td>
<td>DFH-3</td>
<td>~21 500 km</td>
</tr>
<tr>
<td>2009.04.15</td>
<td>GEO</td>
<td>Xichang</td>
<td>CZ-3C</td>
<td>DFH-3</td>
<td>In-orbit maintenance</td>
</tr>
<tr>
<td>2010.01.17</td>
<td>GEO</td>
<td>Xichang</td>
<td>CZ-3C</td>
<td>DFH-3</td>
<td>144.5° E</td>
</tr>
<tr>
<td>2010.06.02</td>
<td>GEO</td>
<td>Xichang</td>
<td>CZ-3C</td>
<td>DFH-3</td>
<td>84° E</td>
</tr>
<tr>
<td>2010.08.01</td>
<td>IGSO</td>
<td>Xichang</td>
<td>CZ-3A</td>
<td>DFH-3</td>
<td>Ascending node: 118° E</td>
</tr>
<tr>
<td>2010.11.01</td>
<td>GEO</td>
<td>Xichang</td>
<td>CZ-3C</td>
<td>DFH-3</td>
<td>160° E</td>
</tr>
<tr>
<td>2010.12.17</td>
<td>IGSO</td>
<td>Xichang</td>
<td>CZ-3A</td>
<td>DFH-3</td>
<td>Ascending node: 118° E</td>
</tr>
<tr>
<td>2011.04.10</td>
<td>IGSO</td>
<td>Xichang</td>
<td>CZ-3A</td>
<td>DFH-3</td>
<td>Ascending node: 118° E</td>
</tr>
</tbody>
</table>

to now, eight satellites have been launched. More details of the missions are shown in table 1. The first two satellites are used mainly for experiment and orbit maintenance.

BeiDou satellites in phase II emit three radio signals: B1, B2 and B3. The characteristics of the signals are shown in table 2.

Due to the difference in functions, the effective loadings of the GEO satellite are somewhat different from IGSO and MEO ones. In addition to the B1/B2/B3 antenna and the laser reflector, the GEO satellite has a C antenna and an L/S antenna to be used in RDSS and two-way satellite time and frequency transfer (TWSTFT) for time synchronization of the ground stations.

The control segment consists of the master control station (MCS), the uplink stations (ULS) and the monitor stations (MS). The main tasks of MCS include the following:

(a) data collection: to collect all the tracking data from all the stations;
(b) data processing: to generate all the satellite navigation data (simply the NAV data), such as the satellite orbits, the clock deviations, ionosphere time delay and differential information, etc;
(c) satellite control: to complete all the navigation satellite services.

Table 2. The radio signal characteristics of the BeiDou Regional Satellite System.

<table>
<thead>
<tr>
<th>Component</th>
<th>Carrier frequency/ MHz</th>
<th>Chip rate/ Mcps</th>
<th>Bandwidth/ MHz</th>
<th>Modulation type</th>
<th>Service type</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1(I)</td>
<td>1561.098</td>
<td>2.046</td>
<td>4.092</td>
<td>QPSK</td>
<td>Open</td>
</tr>
<tr>
<td>B1(Q)</td>
<td>2.046</td>
<td>Authorized</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2(I)</td>
<td>1207.14</td>
<td>2.046</td>
<td>10.23</td>
<td>QPSK</td>
<td>Open</td>
</tr>
<tr>
<td>B2(Q)</td>
<td>10.23</td>
<td>Authorized</td>
<td></td>
<td></td>
<td>Authorized</td>
</tr>
<tr>
<td>B3</td>
<td>1268.52</td>
<td>24</td>
<td>24</td>
<td>QPSK</td>
<td>Authorized</td>
</tr>
</tbody>
</table>

The ULS have two major functions: time synchronizations of satellite clocks and the NAV data uploading. The master station also has these functions.

The MS are well distributed in China, and provide measurements for orbit determination and wide-area differential information. The pseudo-range and carrier phase measurements are transmitted to the master station in real time.

The time and space coordinates are very important for users to get uniform navigation solutions in the case of interoperability of GNSS. The system time of BeiDou is called BDT and the space coordinates are referred to the China Geodetic Coordinate System 2000 (CGCS2000), which is consistent with ITRS on the centimetre level [5, 6].

3. Time scales of the BeiDou System

Time and frequency play significant roles in a GNSS. The characteristics of time and frequency have direct effects on time synchronization, satellite orbit determination and prediction. The measurements obtained and used in a GNSS are also relevant to them. A navigation system must have a good time scale and real physical time and frequency signals to give good performance in time and navigation service. A time and frequency system (TFS) is also a basic component in a GNSS control system required to fulfill its running, processing and controlling jobs.

In BeiDou Navigation System, there is a TFS in the MCS to supply time and frequency signals. The satellite signals are based on the satellite clocks. All the satellites are loaded with high-quality rubidium clocks, which are made by SpectraTime Company, Switzerland, and Chinese companies.

3.1. Definition and realization of BDT

Analogous to the GPS system time (GPST) and different from UTC, the BeiDou system time is an internal and continuous uniform navigation time scale without any leap second. The basic unit of BDT is the SI unit second, and the largest unit is one week defined as 604 800 s. BDT is counted with the week number (WN) and the second of week (SoW), from 0 to 604 799. The zero point of BDT is 1 January 2006 (Sunday) UTC 00h 00m 00s, which means all the numerical values of WN and SoW are equal to zero at that time.

BDT is realized in the ‘composite clocks’ approach and maintained by the TFS located at the MCS. According to the functions, the TFS is mainly composed of five parts: the clock...
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Figure 2. Structure of the BeiDou TFS.

ensemble (CE), the inter-measurement element (IME), the outer comparison element (OCE), the data processing element (DPE) and the signal generation element (SGE). The structure of the TFS is illustrated in figure 2.

The clocks used in time-keeping are more than ten hydrogen masers, which form a CE to provide time and frequency signals. Figures 3(a) and (b) give the performance of a hydrogen clock made by the Shanghai Observatory. The IME provides measurements to the original time and frequency signals from the CE, and gives out the clock differences both in time and frequency in a circular pattern. The deviations of BDT with respect to other time scales, especially to UTC, are obtained by the OCE. The DPE completes the calculation with a given algorithm to give a relative uniform time scale, based on all the information from the IME and OCE, which is called BDT and works as the time reference for the whole navigation system. In line with BDT, the SGE exerts a frequency adjustment to the frequency signal from the master clock (MC), and generates all the real physical time and frequency signals required in the MCS.

The time and frequency transfer chains between the MCS and the National Timing Service Center of the Chinese Academy of Science (NTSC) have been and will further be established. The time offset of BDT with respect to UTC can be obtained indirectly. Figure 4(a) shows the time difference between UTC(NTSC) and BDT obtained by the GPS common view (CV) and figure 4(b) shows the time offset of BDT with reference to UTC given indirectly through UTC(NTSC). Figure 5 shows the time difference between GPST and BDT.

The algorithm used in the BDT calculation is well designed to form a good composite clock. The frequency offset, drift and instability of the free clocks are taken into account. The weight of the clock is determined by its Allan variance (the frequency drift is removed) and a limited weight is also used based on the robust estimation principle [7, 8]. In order to be as consistent as possible with UTC, BDT may be steered with an interposed frequency adjustment after a period of time (more than 30 days) according to the situation, but the quantity of the interposed frequency adjustment is not allowed to be more than $5 \times 10^{-15}$. At present, the performance of BDT is as follows:

Time (frequency) accuracy: $<2 \times 10^{-14}$

Time (frequency) stability: $<1 \times 10^{-14}$/1 day

$<6 \times 10^{-15}$/5 days

$<5 \times 10^{-15}$/10 days

$<6 \times 10^{-15}$/30 days

Time deviation: $|\text{BDT} - \text{UTC}| < 100$ ns (modulo one second).

Figure 3. (a) Clock deviation of the hydrogen clock with the frequency offset removed. (b) Frequency stability of the hydrogen clock (Allan variance).
3.2. Time synchronizations

There are two-way time transfer chains between satellites and ground stations. Each satellite has the capability to perform range measurements with the ground ULS. Then the satellite clock offset with reference to BDT can be precisely determined between satellite and ground stations. The uncertainties of satellite clock offsets are less than 2 ns. Otherwise, the clock offsets can also be obtained through the satellite orbit determination. The offset results must be in accordance with each other. Figures 6(a) and (b) show the deviations of a satellite clock with reference to BDT observed by two-way time and frequency transfer, and in figure 6(b) the average frequency offset is removed. Figures 7(a) and (b) depict its Allan variance and Hadamard variance. Hadamard variance gives information about stability, automatically removing the frequency drift.

The time prediction of satellite clock offset is given by the following known time model:

\[ \Delta T = a_0 + a_1 (t - t_0) + a_2 (t - t_0)^2 + \Delta t_{\text{grav}} \]

where \( \Delta t_{\text{grav}} \) is the relativistic effect expressed as

\[ \Delta t_{\text{grav}} = -\frac{2}{c^2} \sqrt{GM_Ea \cdot \epsilon \sin E}. \]

Here \( GM_E \) is the Earth gravitational parameter, \( c \) the speed of light, \( \epsilon \) the eccentricity, \( a \) the semi-major axis and \( E \) the eccentric anomaly of the satellite orbit. The clock offset parameters \( a_0, a_1 \) and \( a_2 \) are fitted to the observed clock offset data with the binomial model, and are arranged in the NAV data with the orbit parameters. In order to transmit correct navigation signals, the clock offsets are controlled within 1 ms with frequency and phase control.
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Instrumentation of the satellite clock

Figure 7. (a) Observed Allan variance of the satellite clock. (b) Observed Hadamard variance of the satellite clock.

In order to realize time synchronization between the ground stations, high-precision time and frequency transfer chains are built among the MCS, the ULS and some MS, in which the TWSTFT is used [9]. The time comparison of the ground stations can also be realized by the two-way common view of a BeiDou satellite which has a two-channel pseudo-range receiver [10]. The uncertainty of the ground time synchronization is also less than 2 ns. To maintain the coherence of monitor data of navigation satellites between the MS, all the clock offsets are also controlled.

3.3. Time services of the system

The BeiDou System provides time service in three modes which are (1) RDSS one-way time service, (2) RDSS two-way time service and (3) RNSS one-way time service. The RDSS service means that all the time signals are emitted from the master station and transferred by the geostationary satellite to the users, while the RNSS service emits all the signals from the navigation satellites. The so-called ‘one-way time service’ means that all the corrections used in timing are calculated by users themselves on the basis of the NAV data. The ‘two-way time service’ demands that the user responds with a signal back to the master station, and the round-trip time delay is measured by the station and then sent to the user. Currently, with respect to BDT, the uncertainty of the one-way time service is about 100 ns (one sigma), and that of the RDSS two-way time service is about 20 ns (one sigma). With further development of the system, the uncertainties will be improved to 50 ns and 10 ns, respectively.

The NAV data broadcasted by satellites contain the requisite information for relating BDT to UTC. Obviously, the accuracy of the relationship is dependent on the uncertainties of the BDT deviation, the satellite clock offset and the signal propagation time delay. There is a BD timing monitor system in the MCS, which can monitor all the system time services in a closed loop and ensure the validity and usability of time services. Considering the limited deviation of BDT with respect to UTC, the accuracy of time service is sufficient for the users.

4. On the issue of the UTC leap second

Obviously, the existing leap second of UTC is harmful to any navigation satellite system. This is why GPS, Galileo and BeiDou do not use UTC as the reference for steering their system time scales [11]. Indeed, the leap second is not used or is harmful for any system when a continuous time scale is needed. However, we cannot simply make a decision to cancel the leap second or to keep UTC consistent with TAI except for a fixed phase difference. It is well known that the real and natural time is always the sunrise and sunset for human beings and even for animals. The slowing-down of Earth’s rotation will eventually make a significant difference between the new UTC without the leap second and UT1 such that it will not be comfortable for us in a certain far future day. We can say that the difference between UT1 and the new UTC without the leap second will not be a problem for daily life only for a certain period of time, not forever. Then it is conceptually meaningful to continue some ‘coordinated’ function for UTC. The coordination rules should be changed in more convenient ways. In other words, we may retain the word ‘leap’ in UTC, but give up ‘leap second’. For example, we can make the coordinated event only happen at the end of a century.

Briefly, the following tactics may be considered in the reforming of UTC:

(i) keep the name UTC unchanged;
(ii) stop the leap second before the next century;
(iii) keep the continuity of UTC;
(iv) retain the coordinated function for the new UTC without the leap second and UT1 in a more relaxed relation.

5. Conclusions

The BeiDou Navigation Satellite System has been developed as scheduled. Eight satellites have been launched up to now. The system time BDT is stated by WN and SoW from 1 January 2006 UTC 00h 00m 00s. BDT is maintained by the TFS of the master station. The frequency accuracy of BDT is superior to $2 \times 10^{-14}$ and its stability is better than $6 \times 10^{-15}$/30 days.
The satellite time and frequency is realized by rubidium clocks. The time synchronization of the satellite clocks is realized by a two-way time transfer. The measurement uncertainties of the satellite clock offsets are less than 2 ns. The BeiDou System has three modes of time services: (1) RDSS one-way, (2) RDSS two-way and (3) RNSS one-way. The uncertainty of the one-way time service is designed to be less than 50 ns (1 sigma), and that of the two-way time service is less than 10 ns (1 sigma).

As to the future of UTC, it is hoped to stop the leap second to make UTC uniform and continuous, and retain the UTC name unchanged with some reasonable modification of the coordinated function.

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