Research on the Leap Second Adjustment Methods in BDS

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Abstract. Since July 31st 2020, BDS-3 provides service formally, in the open service, BDS-3 reserves old type signals B1I/B3I in BDS-2, and adds new type signals B1C/B2a/B2b. Because users misunderstand how to work out the leap second, some user terminals didn't successfully complete BDT to UTC on June 30th 2015 and 31 December 31st 2016 in time in BDS-2. Compared with BDS-2, BDS-3 has not experience leap second yet, this paper introduces the leap second process in BDS-3 Radio Navigation Satellite Service (RNSS), explains the meanings of time synchronization parameters of BDT to UTC in new type signals, and shows the leap second computational examples, helping user terminals in BDS-3 to complete their leap second adjustment. It is of an active guiding significance and great reference value for user receivers of BDS-3, and is beneficial to BDS-3 timing service promotion.

1. Introduction
BeiDou Navigation Satellite System is called BDS for short, it is divided into three construction and development phases, which is BDS-1, BDS-2 and BDS-3 in sequence [1-2]. Its time reference is The BeiDou Navigation Satellite System Time (BDT), which adopts the second of the international system of units (SI) as the base unit and accumulates continuously without leap seconds. The start epoch of BDT, which is made up of week number and time of week, is 00:00:00 on January 1, 2006 of Coordinated Universal Time (UTC). BDT connects with UTC via UTC(NTSC), and the deviation of BDT to UTC is maintained within 50 nanoseconds (modulo 1 second). The leap second information is broadcast in the navigation message [1-2].

Since December 27th 2012, BDS-2 begins to provide service formally, and there is a positive leap second on June 30th 2015 and December 30th 2016 respectively. However, some user receivers in BDS-2 misunderstand how to calculate a leap second, as a result some user terminals didn't successfully complete BDT to UTC in time in the two leap second adjustments [3-4]. In June 2020, BDS-3 completes all the 30 networked satellites launch mission, and begins to provide service formally on July 31st 2020, which marks that BeiDou-3 global navigation satellite system is build up successfully, up to now, BDS-3 has not experience leap second adjustment yet. China Administration of Satellite Navigation System Office announced BeiDou Satellite Navigation System Interface Control Document of Space Signal for Public Service Signals recently on the website www.beidou.gov.cn, which introduce the relationship between BDT and UTC in detail.
Table 1  Open Service Signals of BDS-3 Navigation Satellite System

| Signals | Broadcasting means | Service types               | Navigation messages | Signal types |
|---------|--------------------|-----------------------------|---------------------|-------------|
| B1I     | 3GEO               | Positioning\ Navigation\ Timing | D1                  | old         |
|         | 3IGSO+24MEO        |                             | D2                  |             |
| B3I     | 3GEO               | Positioning\ Navigation\ Timing | D2                  | old         |
|         | 3IGSO+24MEO        |                             |                     |             |
| B1C     | 3IGSO+24MEO        | Positioning\ Navigation\ Timing | B-CNAV1             | new         |
| B2a     | 3IGSO+24MEO        | Positioning\ Navigation\ Timing | B-CNAV2             | new         |
| B2b     | 3IGSO+24MEO        | Positioning\ Navigation\ Timing | B-CNAV3             | new         |

BDS-3 contains two different services and work models, which are Radio Determination Satellite Service (RDSS for short), as active positioning system, and Radio Navigation Satellite Service (RNSS for short), as passive positioning system, so their leap second parameters, adjustment methods and process are all different. BDS-3 provides RNSS timing service by 3 Geostationary Earth Orbit (GEO) satellites, 3 Medium Earth Orbits (MEO) satellites and 24 Inclined Geo-Synchronous Orbits (IGSO) satellites.

BDS-3 reserves old open service signals B1I/B3I in BDS-2, which broadcast D1 and D2 navigation messages, and adds new open service signals B1C/B2a/B2b, which broadcast B-CNAV1/B-CNAV2/B-CNAV3 navigation messages, as showed in Table 1, and the leap second parameters and calculate methods are different of the old and new signals[5-6].

This paper explains the meanings of time synchronization parameters of BDT to UTC in BDS-3 of the old and new type open service signals, introduces the leap second adjustment methods and process, and shows the leap second computational examples of the new signals, helping user terminals of BDS-3 to complete their leap second adjustment. It is advantageous to promoting BDS-3 timing application, and is of an active guiding significance and great reference value for time synchronization of BDS-3 user receivers.

2. The leap second adjustment methods in BDS-3

2.1. Parameters Description
In BDS-3, RNSS users get BDT to UTC time offset parameters by navigation messages, the offset parameters of old open service signals B1I/B3I are $\Delta_{LS}$, $WN_{LSF}$, $DN$, $\Delta_{LSF}$, $A_{UTC}$, $A_{UTC}$, which are all the same with that in BDS-2. The first four parameters should be focused, and they will update throughout the process. There are detailed explanations in paper [3] and [4].
Table 2  Comparison of the time synchronization parameters of two signal types in BDS-3 RNSS

| Parameters Types | Parameters | Numbers of bits | Scale factor | Effective range | Unit |
|------------------|------------|-----------------|--------------|-----------------|------|
| Old signal parameters | $A_{0/UTC}$ | 32* | $2^{-30}$ | —— | s |
| | $A_{1/UTC}$ | 24* | $2^{-50}$ | —— | s/s |
| | $\Delta_{LS}$ | 8* | 1 | —— | s |
| | $WN_{LSF}$ | 8 | 1 | —— | week |
| | $DN$ | 8 | 1 | 6 | day |
| | $\Delta_{LSF}$ | 8* | 1 | —— | s |
| New signal parameters | $A_{0/UTC}$ | 16* | $2^{-35}$ | —— | s |
| | $A_{1/UTC}$ | 13* | $2^{-51}$ | —— | s/s |
| | $A_{2/UTC}$ | 7* | $2^{-68}$ | —— | s/s2 |
| | $\Delta_{LS}$ | 8* | 1 | —— | s |
| | $\tau_{ot}$ | 16 | $2^4$ | 0–604784 | s |
| | $WN_{ot}$ | 13 | 1 | —— | week |
| | $WN_{LSF}$ | 13 | 1 | —— | week |
| | $DN$ | 3 | 1 | 0–6 | day |
| | $\Delta_{LSF}$ | 8* | 1 | —— | s |

Notes

*Parameters so indicated are two’s complement, with the sign bit (+ or -) occupying the MSB.

**Unless otherwise indicated in this column, effective range is the maximum range attainable with indicated bit allocation and scale factor.

The BDT to UTC time offset parameters of new open service signals B1C\B2a\B2b are $\Delta_{LS}, WN_{LSF}, DN, \Delta_{LSF}, A_{0/UTC}, A_{1/UTC}, A_{2/UTC}, WN_{ot}$, $\tau_{ot}$, and the first four parameters should also be focused. The meanings are as the follow: $A_{0/UTC}$ is the bias coefficient of BDT time scale relative to UTC time scale, $A_{1/UTC}$ is drift coefficient of BDT time scale relative to UTC time scale, $A_{2/UTC}$ is drift rate coefficient of BDT time scale relative to UTC time scale, $\Delta_{LS}$ is current or past leap second count, $WN_{LSF}$ is leap second reference week number, $DN$ is leap second reference day number, $\Delta_{LSF}$ is current or future leap second count, $\tau_{ot}$ is reference time of week, $WN_{ot}$ is reference week number.

The effective range of the time offset parameters are different with the old and new type signals, which are showed in Figure 2. $WN_{LSF}$ in new type signals need not modulo 256. There is a problem of misunderstanding parameters $DN$ for Global Navigation Satellite System (GNSS) receivers, because in BDS-3 the value span of $DN$ is 0-6(from Sunday to Saturday), but the Interface Control Document (ICD) of the Global Positioning System(GPS) by USA and the European GNSS (Galileo) Open Service Signal-In-Space Interface Control Document by European Union regulates that the value span of $DN$ is 1-7(from Sunday to Saturday)\(^{[7-10]}\).
2.2. Equations and mathematics of BDT to UTC in RNSS new signals

The leap second adjustment equations of BDT to UTC in BDS-3 RNSS old signals are the same with BDS-2, there are detailed explanation in paper [3] and [4]. According to the leap second time and the user's present time, three different cases of calculating BDT-UTC time offset are listed as follows in BDS-3 RNSS new signals. Compared with GPS and Galileo, only adding $\Delta_{UTC}$, the equations are generally the same, that enhancing compatibility and interoperability in GNSS receivers.

1) Whenever the leap second time indicated by $WN_{LSF}$ and $DN$ is not in the past (relative to the user’s present time) and the user’s present time does not fall in the time span which starts 6 hours prior to the leap second time and ends 6 hours after the leap second time, $t_{UTC}$ is calculated according to the following equations.

$$t_{UTC} = (t_E - \Delta_{UTC} \text{[modulo 86400]}$$  \hspace{1cm} (1)

$$\Delta_{UTC} = \Delta_{LS} + A_{UTC} + A_{UTC} \times (t_E - t_0) + 604800 \times (WN - WN_0)$$

$$+ A_{UTC} \times (t_E - t_0) + 604800 \times (WN - WN_0)^2$$  \hspace{1cm} (2)

Where, $t_E$ is the BDT time as estimated by the user.

2) Whenever the user’s present time falls within the time span which starts 6 hours prior to the leap second time and ends 6 hours after the leap second time, $t_{UTC}$ is calculated according to the following equations.

$$t_{UTC} = W \text{[modulo(86400 + \Delta_{LSF} - \Delta_{LS})]}$$  \hspace{1cm} (3)

$$W = (t_E - \Delta_{UTC} - 43200) \text{[modulo86400]} + 43200$$  \hspace{1cm} (4)

where, the calculation method of $t_{UTC}$ is shown in equation (2).

3) Whenever the leap second time indicated by $WN_{LSF}$ and $DN$ is in the past (relative to the user’s present time) and the user’s present time does not fall in the time span which starts 6 hours prior to the leap second time and ends 6 hours after the leap second time, $t_{UTC}$ is calculated according to the following equations.

$$t_{UTC} = (t_E - \Delta_{UTC} \text{[modulo 86400]}$$  \hspace{1cm} (5)

$$\Delta_{UTC} = \Delta_{LSF} + A_{UTC} + A_{UTC} \times (t_E - t_0) + 604800 \times (WN - WN_0)$$

$$+ A_{UTC} \times (t_E - t_0) + 604800 \times (WN - WN_0)^2$$  \hspace{1cm} (6)

3. The Leap Second Process in BDS-3

The Leap second adjustment process of RNSS in BDS-3 are generally the same with BDS-2, and there is detailed explanation in paper [3] and [4]. The leap second adjustment processes in BDS-3 are showed in Figure 1.
4. Computational examples in RNSS new type signals

4.1. Before the leap second operation
Assuming that the next leap second time is December 31st 2022, and it is a positive leap second. BDS-3 RNSS new type signals receivers transfer BDT to UTC according to navigation messages. According to the leap second adjustment operation process, 10 weeks before December 31st 2022 (on October 22nd 2022), the BDS-3 begins operation. Before October 22nd 2022, all the parameters stay the last leap second conditions, that is to say, the last leap second is over, and next leap second is not coming, we should choose equations (5), using the parameter $\Delta S_L$ at this time, $\Delta S_L$ is the same with $\Delta S_LF$.

4.2. During the leap second operation
4.2.1. Between 10 weeks prior to the leap second time and 6 hours prior to the leap second time
On 10 weeks prior to December 31st 2022 (on October 22nd 2022), the BDS-3 begins operation, some RNSS navigation message parameters $WN_{LSF \ \ \ DN \ \ \ M_{LSF}}$ update, at this time, the leap second time indicated by $WN_{LSF}$ and $DN$ is not in the past (relative to the user’s present time) and the user’s present
time does not fall in the time span which starts 6 hours prior to the leap second time and ends 6 hours after the leap second time, we should choose equations (1), using the parameter $L_{St}$.

At BDT 882 week 345604 seconds (0h 0m 4s 1 December 2022 BDT), the time synchronization parameters in navigation messages are $\Delta L_{S} = 4$, $W_{NLs} = 886$, $DN = 6$, $\Delta L_{SF} = 5$, $WN = 882$, estimated parameters are $A_{QUTC} = -2 \times 10^{-9}$, $A_{UTC} = 3 \times 10^{-13}$, $A_{UTC} = 1 \times 10^{-16}$, $W_{Na} = 882$, $t_{oa} = 345600$.

$$t_{UTC} = (t_{E} - \Delta L_{UTC}) \mod 864000$$

$$= [t_{E} - (\Delta L_{S} + A_{QUTC} + A_{UTC} \times (t_{E} - t_{oa}) + 604800 \times (WN - W_{Na})) + A_{UTC} \times (t_{E} - t_{oa}) + 604800 \times (WN - W_{Na}))^2] \mod 864000$$

$$= [345604 - 2 \times 10^{-9} + 1.2 \times 10^{-12} + 4 \times 10^{-16}] \mod 864000$$

$$= 0$$

So, we get 0h 0m 0s 1 December 2022 UTC, then the difference value of BDT to UTC is 4.

**4.2.2. Within 6 hours prior to the leap second time and ends 6 hours after the leap second time**

When the user’s present time falls within the time span which starts 6 hours prior to the leap second time and ends 6 hours after the leap second time, we should choose equations (3), using the parameters $L_{St}$ and $L_{SFt}$.

At BDT 887 week 4 seconds (0h 0m 4s 1 January 2023 BDT), the time synchronization parameters in navigation messages are $\Delta L_{S} = 4$, $W_{NLs} = 886$, $DN = 6$, $\Delta L_{SF} = 5$, $WN = 887$, estimated parameters are $A_{QUTC} = 3 \times 10^{-9}$, $A_{UTC} = 1 \times 10^{-13}$, $A_{UTC} = -2 \times 10^{-16}$, $W_{Na} = 887$, $t_{oa} = 0$.

$$\Delta UTC = \Delta L_{S} + A_{QUTC} + A_{UTC} \times (t_{E} - t_{oa}) + 604800 \times (WN - W_{Na})$$

$$+ A_{UTC} \times (t_{E} - t_{oa}) + 604800 \times (WN - W_{Na}))^2] \mod 864000$$

$$= 4 + 3 \times 10^{-9} + 4 \times 10^{-13} - 8 \times 10^{-16}$$

$$= 4 + 3.003992 \times 10^{-9}$$

$$t_{UTC} = [t_{E} - \Delta UTC] \mod 864000$$

$$= [t_{E} - 432000 \mod 864000 + 432000] \mod 864000$$

$$= [432000 + 432000] \mod 864000$$

$$= 86400$$

So, we get 23h 59m 60s 31 December 2022 UTC, adding the 61st second, then the difference value of BDT to UTC is 5.

**4.2.3. After 6 hours after the leap second time**

After 6 hours after the leap second time, the parameter $\Delta L_{S}$ broadcast by BDS-3 satellites begins to update. At this time, the leap second time indicated by $W_{NLs}$ and $DN$ is in the past (relative to the user’s present time) and the user’s present time does not fall in the time span which starts 6 hours prior to the leap second time and ends 6 hours after the leap second time, we should choose equations (5), using the parameter $L_{SFt}$.

At BDT 887 week 21605 seconds (6h 0m 5s 1 January 2023 BDT), the time synchronization parameters in navigation messages are $\Delta L_{S} = 5$, $W_{NLs} = 886$, $DN = 6$, $\Delta L_{SF} = 5$, $WN = 887$, estimated parameters are $A_{QUTC} = -1 \times 10^{-9}$, $A_{UTC} = -2 \times 10^{-13}$, $A_{UTC} = 4 \times 10^{-16}$, $W_{Na} = 887$, $t_{oa} = 21600$.

$$t_{UTC} = (t_{E} - \Delta UTC) \mod 864000$$

$$= [t_{E} - (\Delta L_{S} + A_{QUTC} + A_{UTC} \times (t_{E} - t_{oa}) + 604800 \times (WN - W_{Na})) + A_{UTC} \times (t_{E} - t_{oa}) + 604800 \times (WN - W_{Na}))^2] \mod 864000$$

$$= [21605 - 1 \times 10^{-9} - 1 \times 10^{-12} + 2 \times 10^{-15}] \mod 864000$$

$$= 21600$$

So, we get 6h 6m 0s 1 January 2023 UTC, then the difference value of BDT to UTC is 5.
4.3. After All Leap Second Parameters Updated

When all the parameters broadcast by all the BDS-3 satellites have updated, that is to say, this leap second is over, and the next leap second is not coming. At this time, the leap second time indicated by $\omega_{LSF}$ and $\Delta N$ is in the past (relative to the user’s present time) and the user’s present time does not fall in the time span which starts 6 hours prior to the leap second time and ends 6 hours after the leap second time, we should choose equations (5), using the parameter $\Delta LSF$, and $\Delta L$ is the same with $\Delta LSF$.

5. Summary

Along with BeiDou Satellite Navigation System built up, BDS gets great application and development, the number of BDS timing receivers increase rapidly, which are used in many fields around the world, such as communications, electricity, finance, military, mapping marine fishery and so on. So, it is very important to complete leap second adjustment successfully. During the last two leap second adjustments on 30 June 2015 and 31 December 2016, some BDS-2 user terminals didn't successfully complete BDT to UTC. This paper explains the meanings of time offset parameters of BDT to UTC in BDS-3 of the old and new type open service signals, introduces the leap second adjustment methods and process in RNSS, and shows the leap second computational examples of the new type signals in BDS-3, helping user terminals of BDS-3 to complete their leap second adjustment. It is of an active guiding significance and great reference value for time synchronization of BDS-3 timing user receivers, and is advantageous to promoting BDS-3 timing application.

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