International UTC TAI comparison based on BDS PPP

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Abstract

The BeiDou Navigation Satellite System (BDS), developed by China, has provided free official service for the Asia-Pacific region since 2012. With the development of BDS, BDS-based time transfer has become an important research direction in BDS application fields. Currently, the primary method for BDS-based time transfer is BDS Common View (BDS CV), which can achieve nanosecond-level accuracy. Therefore, we investigate the performance of time transfer based on BDS Precise Point Positioning (PPP) for UTC/TAI computation. In this contribution, we focus on UTC/TAI comparison based on BDS PPP using developed quad-constellation GNSS software called National Time System Center' s (NTSC) Bernese. A long-term data analysis is presented. The experiments include two parts: (1) The reliability of the software and multi-GNSS products; (2) The performance of BDS PPP for International UTC/TAI comparison. The experimental results reveal that the accuracy of NTSC' s Bernese GPS PPP can reach approximately 0.1 ns relative to BIPM TAI PPP solutions. Compared with BIPM TAI PPP solutions, the accuracy of GPS PPP solutions can achieve approximately 0.2 ns using multi-GNSS precise products, such as GBM and COM. For BDS PPP solutions, the GPS PPP solutions are regarded as reference values. It is demonstrated that the accuracy of time transfer based on BDS PPP can reach better than 1 ns for UTC/TAI comparison for the statistics of 30-day arc solutions, while 0.1 ns magnitude can be achieved for the statistics of daily solutions due to the influence of day boundary discontinuity. Moreover, four different processing strategies of BDS PPP are tested, which include tropospheric delay fixed, tropospheric delay and coordinates fixed, coordinates fixed, and BDS-only. Results show that comparable accuracy can be achieved for the four processing strategies. Hence, one can conclude that time transfer based on BDS-only PPP shows good performance for UTC/TAI computation.

Full Text

Preamble

International UTC and TAI Comparison Based on BDS PPP

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Abstract

The BeiDou Navigation Satellite System (BDS), developed by China, has provided free official service for the Asia-Pacific region since 2012. With the development of BDS, BDS-based time transfer has become an important research direction in BDS application fields. Currently, the main method for BDS-based time transfer is BDS Common View (BDS CV), which can achieve nanosecond-level accuracy according to previous studies by other researchers. In this contribution, we further investigate the performance of time transfer based on BDS Precise Point Positioning (PPP) for UTC/TAI computation. Our investigation employs BDS PPP using developed quad-constellation GNSS software called National Time System Center' s (NTSC) Bernese, and presents a long-term data analysis. Numerical tests carried out using more than 730 days of data from 14 stations from January 1, 2015, to January 1, 2017, suggest three major findings. First, compared with BIPM TAI PPP solutions, the uncertainty of NTSC' s Bernese GPS PPP can reach about 0.1 ns using IGR products and about 0.2 ns using multi-GNSS precise products such as GBM and COM. Second, with GPS PPP solutions regarded as reference values, it is demonstrated that the uncertainty of time transfer based on BDS PPP can reach better than 1 ns for UTC/TAI comparison in 30-day arc solutions, while 0.1 ns magnitude can be achieved for daily solutions due to the influence of day boundary discontinuity. Third, four different processing strategies for BDS PPP—including tropospheric delay fixed, tropospheric delay and coordinates fixed, coordinates fixed, and BDS-only—are tested. Results show that comparable uncertainty can be achieved across all four processing strategies. Hence, one can conclude that time transfer based on BDS-only PPP shows good performance for UTC/TAI computation.

Keywords: Precise point positioning; BDS; UTC/TAI comparison; Bernese

1 Introduction

It has long been known that the GPS Common-View (CV) time and frequency transfer method was proposed in the 1980s, with Allan using pseudorange observations and explicit differencing of GPS data collected at two international timing laboratories [?]. The uncertainty of CV time transfer can reach a few nanoseconds. Nowadays, GPS CV has been widely used for time and frequency transfer by international time laboratories due to its low cost and attractive accuracy. However, the Common View method is known to be affected by the distance between station pairs or time-links [?].

Thanks to the International GNSS Service (IGS), which has provided precise orbits and clock products [?], another technique called All in View (AV) was proposed by Petit and Jiang [?]. Unlike CV, this method is not subject to the distance between different international time laboratories and can achieve comparable accuracy. Unfortunately, the uncertainty of both GPS CV and GPS AV is limited by pseudorange observations. Consequently, GPS Precise Point Positioning (PPP) [?], which uses a combination of pseudorange and phase observations, has been applied [?, ?]. The uncertainty of GPS PPP can reach sub-nanosecond magnitude as well as greater frequency stability in the short term. At the BIPM, this technique has been operationally used to compute time links for International Atomic Time (TAI) since September 2009 and now concerns over 50% of the more than 70 laboratories contributing to TAI and UTC [?, ?].

China is developing the BeiDou Navigation Satellite System (BDS), which adopts its own time system (BeiDou Time, BDT) and coordinate system (China Geodetic Coordinate System 2000, CGCS2000) [?]. When fully deployed, the BDS constellation will provide worldwide coverage based on 35 satellites including 5 Geostationary Earth Orbit (GEO) satellites, 27 Medium Earth Orbit (MEO) satellites, and 3 Inclined Geosynchronous Satellite Orbit (IGSO) satellites. Currently, the constellation comprises 15 satellites total, with 5 satellites in each group. The GEO and IGSO satellites can be observed from the Asia-Pacific region and parts of Europe. With the development of BDS, BDS-based time transfer has become an important research direction in BDS application fields. At present, the main method for BDS-based time transfer is BDS Common View (BDS CV), which can reach nanosecond magnitude [?, ?, ?, ?]. In addition, many scholars have conducted research on time transfer based on BDS PPP [?, ?].

However, the above research has only focused on the method of time transfer and has not applied BDS PPP to Universal Time Coordinated (UTC) and International Atomic Time (TAI) comparison, nor has there been long-term data analysis for BDS PPP time transfer. In this contribution, based on Bernese 5.2 [?], which has been developed for quad-constellation GNSS data processing and is called National Time System Center' s (NTSC) Bernese, we investigate UTC/TAI comparison based on BDS PPP and present a long-term data analysis. We expect good performance from BDS PPP time transfer for UTC/TAI comparison.

In this work, observation data from 14 stations from international time laboratories or globally distributed stations from the IGS Multi-GNSS Experiment (MGEX) network [?] are selected. The datasets are processed using BDS PPP technique from DOY 1, 2015, to DOY 1, 2017, to investigate the reliability of BDS PPP for international UTC/TAI comparison. The remainder of this paper is organized as follows. Section 2 describes the ionosphere-free (IF) observation model of PPP. Section 3 provides a brief statement about the data and processing strategy. Section 4 first verifies the feasibility of NTSC' s Bernese 5.2 software for UTC/TAI comparison by comparing the results of GPS PPP provided by the Bureau International des Poids et Mesures (BIPM). Second, the reliability of precise products such as GBM and COM (ftp://cddis.gsfc.nasa.gov/pub/gps/products/mgex/) provided by MGEX are verified. Finally, the results of BDS PPP are analyzed and compared with GPS PPP. Section 5 draws the conclusions.

2 Ionosphere-Free PPP Observation Model

The undifferenced ionosphere-free observations for pseudorange P and carrier phase Φ can be written as follows:

$$
\begin{aligned}
P_{IF}^{s} &= \rho_r^s + c(dt_r - dt^s) + T_r^s + \varepsilon_{P_{IF}}^s \\
\Phi_{IF}^{s} &= \rho_r^s + c(dt_r - dt^s) + T_r^s + \lambda_{IF} N_{IF}^s + \varepsilon_{\Phi_{IF}}^s
\end{aligned}
$$

where indices s and r refer to the satellite and receiver, respectively. ρ_r^s denotes the geometric distance between the satellite and receiver. dt_r and dt^s are the clock errors of the receiver and satellites, respectively. N_{IF}^s is the float ambiguity. λ_{IF} is the wavelength. T_r^s refers to the slant tropospheric delay. $\varepsilon_{P_{IF}}^s$ and $\varepsilon_{\Phi_{IF}}^s$ include the measurement noise and multipath error for the ionosphere-free pseudorange and carrier phase observations.

Traditional PPP is usually used in geodetic survey [?, ?, ?]. For time and frequency transfer, receivers at different stations are connected to their time and frequency references, such as the 1 PPS signal and 5/10 MHz frequency signal [?]. Figure 1 [Figure 1: see original paper] shows the PPP time transfer principle. Based on the atomic clock, receivers acquire phase and code observations from all satellites in view. Each station calculates its clock difference between UTC(i) and IGST. As shown in Figure 1, the time difference UTC(i) - UTC(j) between station A and station B can be calculated, expressed as:

$$
\mathrm{UTC}(i) - \mathrm{UTC}(j) = (\mathrm{UTC}(i) - \mathrm{IGST}) - (\mathrm{UTC}(j) - \mathrm{IGST}) \tag{3}
$$

It should be noted that the clock errors calculated by PPP, including hardware delay, should be corrected. Because the correction method is complex, the correction process will not be presented herein.

3.1 Dataset

The BIPM provides 30-day arc solutions of GPS PPP using IGR products from IGS for international time laboratories every month (ftp://ftp2.bipm.org/pub/tai/). To investigate the feasibility of NTSC' s Bernese 5.2 software for international UTC/TAI comparison, the results provided by BIPM are used as external reference values. Figure 2 [Figure 2: see original paper] displays the geographical distribution of the 14 stations used in this work, which includes 7 stations from international time laboratories and 7 MGEX stations. It should be noted that the 7 stations from international time laboratories are used to verify the feasibility of NTSC' s Bernese 5.2 software and the reliability of GBM or COM products. Currently, few stations in international timing laboratories can observe BDS satellites, such as BRUX and ROAP.

Therefore, the feasibility of BDS PPP for international UTC/TAI comparison is tested using the other 7 MGEX stations and some stations from international timing laboratories. The selected MGEX stations are all connected to high-performance atomic clocks. Table 1 summarizes the information for these stations. More than 730 days of data from these stations from January 1, 2015, to January 1, 2017, are analyzed.

3.2 Processing Strategy

Table 2 summarizes the detailed processing strategy for GPS PPP and BDS PPP. IGR and COM precise orbit and clock products at intervals of 15 min and 5 min, respectively, are employed. The interval of GBM products is 5 min and 30 s, respectively. Note that differential code bias (DCB) is corrected using DCB products (P1C1) provided by the Center for Orbit Determination in Europe (COD) for GPS PPP, while DCB does not need to be corrected for BDS PPP based on ionosphere-free linear combination (LC) observations because ionosphere-free LC pseudorange is used for satellite clock estimation [**?**, **?**].

Table 2 summarizes the PPP processing strategies, including: number of stations (GPS: 32; BDS: 14); number of satellites; estimator (Least Squares (LSQ) estimator); observables (undifferenced ionosphere-free combined observables); signal selection (GPS: L1/L2; BDS: B1/B2); sampling rate; elevation cutoff (e > 30°); observation weighting (a priori precision 0.6 m and 0.001 m for raw code and phase observations, respectively); elevation-dependent weighting; phase wind-up correction [**?**]; tropospheric delay (ZHD corrected with GMF model [**?**], ZWD estimated as continuous piecewise linear function with 2 h parameter spacing using GMF mapping function [**?**]); tidal displacements (solid Earth tide, pole tide, ocean tide loading corrections); relative effect; Sagnac effect; satellite antenna PCOs and PCVs (PCO and PCV correction for GPS from igs08.atx); receiver clock (estimated as white noise); station coordinates (estimated as static); phase ambiguities (estimated as float values); and IERS Conventions 2010 [?].

The main experiments are displayed in Table 3 . For solutions 1, 2, and 3, GPS PPP is tested using different precise products, with BIPM TAI PPP solutions regarded as external reference values to verify the reliability of time transfer using the software and multi-GNSS precise products for international UTC/TAI comparison. To evaluate the performance of BDS PPP time transfer for UTC/TAI comparison, solutions 4 and 8 are designed to prove the performance of BDS PPP on international UTC/TAI comparison and investigate the effect of using different products. Generally, PPP parameters include coordinates, receiver clock error, tropospheric delay, and float ambiguity. To investigate the impact of other parameters on clock error solutions, experiments for solutions 4, 5, 6, and 7 are conducted.

The daily coordinates of these stations are estimated using IGS final orbit and clock products in static mode or IGS weekly SINEX (Solution Independent Exchange format) solutions. The daily solution is then applied to all tests in this contribution. Note that the GPS PPP solutions will be regarded as external reference values for proving the feasibility of BDS PPP for international UTC/TAI comparison in solutions 4-8, as no other more reliable results are available as external references at present.

4.1 The Reliability of the Software and Multi-GNSS Products

Figure 3 [Figure 3: see original paper] shows the differences between BIPM PPP and NTSC's Bernese GPS PPP solutions for 6 stations using IGR products. The clock differences between BIPM TAIPPP and more than two years of Bernese GPS PPP solutions for a single station using IGR products are illustrated in Figure 3. Note that daily arc solutions are obtained from Bernese software in this contribution. The solutions for other sites show similar features at different times and are thus not presented herein. The figure confirms that the differences are basically stable between -0.2 and 0.2 ns. However, the solutions are poor at the NIST station (Figure 3(e)), mainly due to poor observation quality. On the other hand, obvious day boundary discontinuity can be seen in Figure 3(f), which may be caused by pseudorange noise [?]. The day boundary discontinuity will not be mitigated by using 30 s clock products. Many scholars have researched methods to mitigate this issue [?], but we will not elaborate on it herein.

To evaluate the uncertainty of PPP solutions, the authors introduce standard deviations (STD) as evaluation criteria. The BIPM PPP solutions are regarded as external reference values in this section. Month solutions are used as a data arc for statistics. Figure 3 illustrates the statistics of solutions for 6 sites from international time laboratories, computed with BIPM PPP solutions and NTSC' s Bernese GPS PPP solutions, over the 28-month period from January 1, 2015, to May 1, 2017. The figure confirms the announced uncertainty of NTSC' s Bernese GPS PPP-based UTC/TAI comparison: the STD of clock differences reaches about 0.1 ns. As shown in Figure 3, some statistics are poor, mainly due to problems at the NIST and ROAP sites. Compared with BIPM TAIPPP solutions, NTSC' s Bernese solutions show good performance overall, which also illustrates the reliability of the software from another perspective.

Figures 4 [Figure 4: see original paper] and 5 [Figure 5: see original paper] present the clock differences between BIPM TAI PPP and NTSC' s Bernese GPS PPP solutions for four time-links using GBM or COM products. These figures indicate that the solutions are relatively stable and can achieve better uncertainty. Figure 5 depicts solutions using COM products, with stable results shown in (a), (b), and (d). Poor performance is shown in Figure 4(c) and Figure 5(c) for the same reasons as stated before. It should be mentioned that several gaps appear in Figures 4 and 5, mainly because the receiver for TAI PPP provided by BIPM at the PTBB station and the receiver for PTBB provided by IGS are inconsistent during those two months.

Figure 6 [Figure 6: see original paper] displays the statistics of 30-day arc solutions using GBM or COM products for five time-links. As shown in Figure 6, the uncertainty of the solutions can achieve better than 0.2 ns for different multi-GNSS products, except for PTBB-NIST and PTBB-ROAP. Different uncertainty can be obtained from different time-links, mainly due to varying observation conditions, receivers, antennas, and external clocks.

4.2 The Performance of BDS PPP

Figure 7 [Figure 7: see original paper] shows the clock differences between BDS PPP and GPS PPP for four time-links using GBM 30 s products. It should be mentioned that the BDS PPP solutions in Figure 7 have tropospheric delay and coordinates fixed. An offset appears in Figure 7(a), caused by adjustment of the local clock. Apart from these two points, BDS PPP solutions achieve good performance compared with GPS PPP solutions. However, a system bias exists between BDS PPP and GPS PPP solutions because the different frequencies and signal structures of individual GNSS result in different code bias values in a single multi-GNSS receiver. These differences are usually called inter-system biases (ISB) for code observations [?]. The main factors affecting the uncertainty of BDS PPP solutions include the receiver, antenna, observation environment, external clock, satellite geometry structure, and processing strategies. Comparing Figure 7(a) and Figure 7(b), the uncertainty on DLF1-BRUX shows better performance. The root mean squares (RMS) of multipath are 0.43 m and 0.34 m at DLF1 and GMSD stations on DOY 3, 2016, respectively. The receiver type and external clock are the same at DLF1 and GMSD according to Table 2. The sky plot of BDS constellations at DLF1 and GMSD stations is presented in Figure 8 [Figure 8: see original paper]. In addition, the average Geometric Dilution of Precision (GDOP) values are 10.9 and 2.9 at DLF1 and GMSD, respectively. Hence, the poor performance of GMSD-BRUX may be due to the poor performance of the external clock at GMSD. Compared with Figure 7(a), the uncertainty of solutions in Figure 7(d) is poor, mainly due to poor observation conditions. Although the uncertainty differs across time-links, BDS PPP solutions remain relatively stable for UTC/TAI comparison in the current state of the BeiDou system.

To investigate the uncertainty of BDS PPP time transfer, GPS PPP solutions are regarded as external reference values. The 30-day arc solutions are analyzed for all time-links according to BIPM strategies. All statistics are illustrated in Figure 9 [Figure 9: see original paper]. As shown in Figure 9, the uncertainty of BDS PPP solutions can be better than 1 ns for all time-links. Some results are poor; for example, the poor performance of WTZR-BRUX is caused by observation conditions and the characteristics of the atomic clock. Overall, BDS PPP time transfer shows good performance for UTC/TAI comparison.

The uncertainty of time transfer based on BDS PPP is affected not only by observation conditions, receiver, antenna, and external clock but also by processing strategies and precise products. Therefore, four processing strategies are investigated and listed in Table 3. The STD values are illustrated in Figure 10 [Figure 10: see original paper]. Compared with BDS PPP-only, the other three processing strategies show good performance. The best uncertainty for BDS PPP can be achieved with tropospheric delay fixed or with both tropospheric delay and coordinates fixed. However, the differences among the four processing strategies are very small, only about 0.1 ns. One can conclude that uncertainty better than 1 ns can be achieved based on BDS PPP without external auxiliary conditions. On the other hand, the uncertainty of precise products is also a main factor in BDS PPP time transfer. Hence, the comparison of COM and GBM products is illustrated in Figure 11 [Figure 11: see original paper]. The interval sample of COM and GBM clock products is used in this section. Compared with GBM products, BDS PPP shows relatively poor performance with COM products because COM products contain no GEO satellite information and have different product characteristics.

Currently, day boundary discontinuity remains an unsolved problem. The statistics of 30-day arc solutions include the error from day boundary discontinuity. Therefore, the statistics of daily solutions are investigated. As shown in Figure 12 [Figure 12: see original paper], the statistics of daily solutions for time-links are presented. Solutions for other time-links show the same feature and are not described in detail. Overall, the uncertainty can reach better than 0.1 ns, although some results are poor, mainly due to observations and product accuracy.

5 Conclusion

In this contribution, we focus on the performance of time transfer based on BDS PPP for TAI/UTC computation. Fourteen stations, including 7 stations from international time laboratories and 7 MGEX stations, are used in this study. We analyzed more than 880 days of data from these stations from January 1, 2015, to May 1, 2017. First, the reliability of the software and multi-GNSS products is analyzed, with BIPM TAIPPP solutions regarded as external reference values. Then, the performance of BDS PPP and comparisons of four processing strategies are presented, with GPS PPP solutions regarded as external reference values in this section.

Compared with BIPM TAIPPP solutions, the uncertainty of NTSC' s Bernese software solutions can achieve better than 0.1 ns using the same products and observation data, demonstrating the reliability of the software. On the other hand, to verify the reliability of multi-GNSS precise products, BIPM TAIPPP solutions using IGR products are regarded as external reference values. Since different precise clock products have different reference clocks, time-link solutions are presented. Comparative analysis shows that uncertainty can reach about 0.2 ns using multi-GNSS products. One can conclude that multi-GNSS products can be used for PPP time transfer and achieve good performance.

To investigate the performance of BDS PPP for UTC/TAI comparison, GPS PPP solutions are regarded as reference values. Comparative analysis shows that the uncertainty of BDS PPP can reach better than 1 ns using GBM products. The uncertainty is affected by many factors, such as the receiver, antenna, observation environment, external clock, satellite geometry structure, and processing strategies. Therefore, four processing strategies are tested: coordinates fixed, tropospheric delay fixed, coordinates and tropospheric delay fixed, and BDS-only. Results show that comparable uncertainty can be achieved across all four processing strategies. Hence, one can conclude that comparable uncertainty for time transfer can be obtained based on BDS-only PPP for UTC/TAI computation.

From the above discussion, for 30-day arc solutions, the conclusion can be reached that the uncertainty of time transfer based on BDS-only PPP can reach better than 1 ns for UTC/TAI computation, while 0.1 ns magnitude can be achieved for daily solutions.

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