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Evaluation of BeiDou time transfer over multiple inter-continental baselines towards UTC contribution

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Abstract

A road map for the implementation of the BeiDou Navigation Satellite System (BDS) time transfer in coordinated universal time (UTC) has been drawn up, including a pilot experiment to evaluate BDS time transfer on multiple baselines. In the pilot experiment, several laboratories contributing to UTC have been equipped or are planned to be equipped with BDS time and frequency transfer receivers made by the National Institute of Metrology (NIM, Beijing). In the first phase, concentrating on the evaluation for the global capacity of BDS time transfer, the experiments have been implemented on multiple inter-continental baselines, involving NIM, Bureau International des Poids et Mesures (BIPM, Sevres), other institutes in China and the Czech Republic, and stations from the International Global Navigation Satellite System (GNSS) Service (IGS) network. The satellite signal coverages at various sites were characterized for satellite number, satellite elevation and satellite azimuth. Stability and accuracy of time transfer by BDS have been evaluated, based on common clock difference and multiple inter-continental baselines experiments, concluding agreement between BDS time transfer and GPS time transfer and a time stability of less than 1 ns at some thousand seconds averaging time at the present satellite coverage of BDS.

Keywords: time transfer, BeiDou, GNSS, time and frequency, metrology

(Some figures may appear in colour only in the online journal)

1. Introduction

To date, a total of 31 navigation satellites have been launched in the BeiDou Navigation Satellite System (BDS), including twelve medium earth orbit (MEO) satellites, seven geostationary orbit (GEO) satellites, eight inclined geosynchronous satellite orbit (IGSO) satellites and four experimental satellites. However, the global constellation of the BDS system is not finished. There are fourteen satellites including five GEO satellites, six IGSO satellites and three MEO satellites for the present basic space constellation of the second generation of the BDS system (BDS-2) [1] and eight satellites for the third generation of the BDS system (BDS-3). It is planned that the constellation of BDS will be accomplished with 35 satellites around 2020, after which much better performance should be expected. Since 2012, BDS Signal in Space Interface Control Document (ICD)-Open Service Signal B1i and B2i (Version 2.1) [2] in BDS-2 system has been published for formal use.

Research on time and frequency transfer using BDS has made notable progress in recent years. In 2013 [3], code-based and carrier phase BDS time transfer were introduced using a prototype receiver, which was based on one original equipment manufacturer (OEM) module; the uncalibrated receiver was synchronized with an external reference, and common clock difference (CCD) and short baseline experiments have been implemented and evaluated. In 2014 [4], a frequency transfer method using the carrier phase solutions of only the GEO satellites in the BDS system was developed, followed by an experiment on a long baseline using MGEX (Multi-GNSS (Global Navigation Satellite System) Experiment) data from the International GNSS Service (IGS) [5]. In 2016 [6], the unpublished version of R2CGGTTS software compatible with BDS measurement was developed, which converts to CGGTTS (Common Generic GNSS Time Transfer Standards) files from receiver independent exchange format (Rinex) files; it was then tested on continental baselines, inside Europe, and the detailed complete evaluation has been performed using this software from Rinex observation files. The strategy document of the Consultative Committee for Time and Frequency (CCTF) [7] establishes as one target the development of a multi-constellation clock comparison. This, combined with the rapid development of BDS, has prompted studies on BDS time transfer among various sites, especially on multiple inter-continental baselines, towards coordinated universal time (UTC) contribution. Thus, the evaluation of BDS time transfer for UTC contribution, particularly over multiple inter-continental baselines at the global scale, comes to the fore.

A new multi-GNSS version of the time transfer system, NIM-TF-GNSS-3, has been developed at the National Institute of Metrology, Beijing (NIM). Finished in mid-2016, it is capable of time and frequency transfer with a global positioning system (GPS) GPS, GLONASS (GLObal NAvigation Satellite System) and BDS. Two of these new systems were installed at the BIPM in 2017, as part of a pilot experiment originally planned to investigate the time transfer performance of BDS satellites over long baselines—in particular, the Asia-Europe link. Since the end of July 2017, the experiment has been extended to other institutes, which have been selected to construct a good geographical distribution. These institutes will operate the receivers provided by the NIM. A software suite called RinCGG has been developed to generate CGGTTS (V2E) files from Rinex files for wider application and evaluation of BDS time transfer compared to GPS time transfer. It can process BDS, GPS, GLONASS and GALILEO measurements. In addition, another extension of the pilot experiment will be to test and validate BDS time transfer for implementation in UTC.

A road map for the evaluation and implementation of BDS time transfer for UTC and related outcomes was developed in September 2017. The first step consists of an evaluation of the performance and feasibility of BDS time transfer for UTC contribution in the pilot experiment organized by the NIM and the BIPM (Bureau International des Poids et Mesures, Sevres) within an experimental network which also includes the OP (Observatoire de Paris, Paris), PTB (Physikalisch-Technische Bundesanstalt, Braunschweig), NIST (National Institute of Standards and Technology, Boulder), VNIIFTRI (Russian Metrological Institute of Technical Physics and Radio Engineering, Moscow, SU in BIPM Circular T), USNO (United States Naval Observatory, Washington, DC), all of which operate NIM-made receivers and perform time comparison over multiple inter-continental baselines. At present,

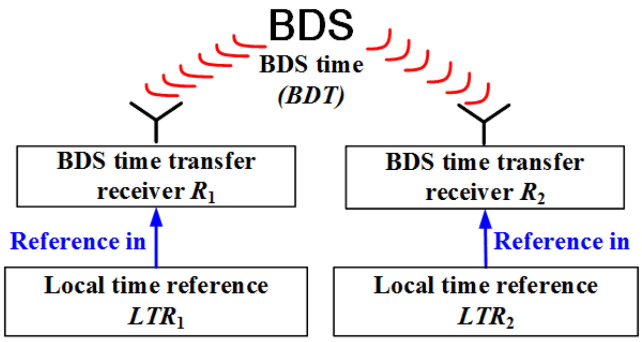

Figure 1. Time and frequency transfer by BDS.

NIM-TF-GNSS-3 receivers have been operated at the NIM, the BIPM, the OP and the PTB. More data will be incorporated as soon as available from the other participants. The first evaluation presented in this paper involved the BIPM, the NIM, one Chinese institute operating one NIM-made receiver, one Czech institute and a few IGS tracking sites.

2. Implementation of BDS time transfer

2.1. Principles

The BDS-2 system has been formally used for positioning, navigation and timing since 2012. The time reference for the BDS is BDS Time (BDT), which adopts the international system of units (SI) 'second' as the basic unit for continuous accumulation, without inserting leap seconds. The initial epoch for BDT is 00:00:00 on 1 January 2006 of UTC. BDT offset with respect to UTC is maintained within 100 ns (modulo 1 s). Leap seconds are broadcast in a navigation message [2]. Thus, the difference between International Atomic Time (TAI) and BDT is within 100 ns plus a constant 33 s, while the integral number difference of seconds between BDT and UTC has been 4 since 1 January 2017 and will remain so until the next insertion of a leap second.

Presently, time and frequency transfer by BDS is mainly through three types of signal: B1i code, L3B code (ionosphere-free code in line with the linear combination of B1i and B2i codes) and carrier phase. The basic principle is shown in figure 1. BDS time transfer receivers R_1 and R_2 are separately referenced to the corresponding local time LTR_1 and LTR_2 at the two stations [3]. The reference methods may be different in terms of the operation modes of the receivers [8]. ΔT_1 and ΔT_2 represent separately the differences between the local time reference at each station and BDT; the difference between LTR_1 and LTR_2 can be calculated by differentiating ΔT_1 and ΔT_2 as in equations (1)–(3):

$$\Delta T_1 = LTR_1 - \mathrm{BDT} \tag{1}$$

$$\Delta T_2 = LTR_2 - \mathrm{BDT} \tag{2}$$

$$LTR_1 - LTR_2 = \Delta T_1 - \Delta T_2. \tag{3}$$

In time transfer by BDS, some parameters related to the Earth's reference frame are worth mentioning. These are the Earth's gravitational constant and the Earth's rotation rate,

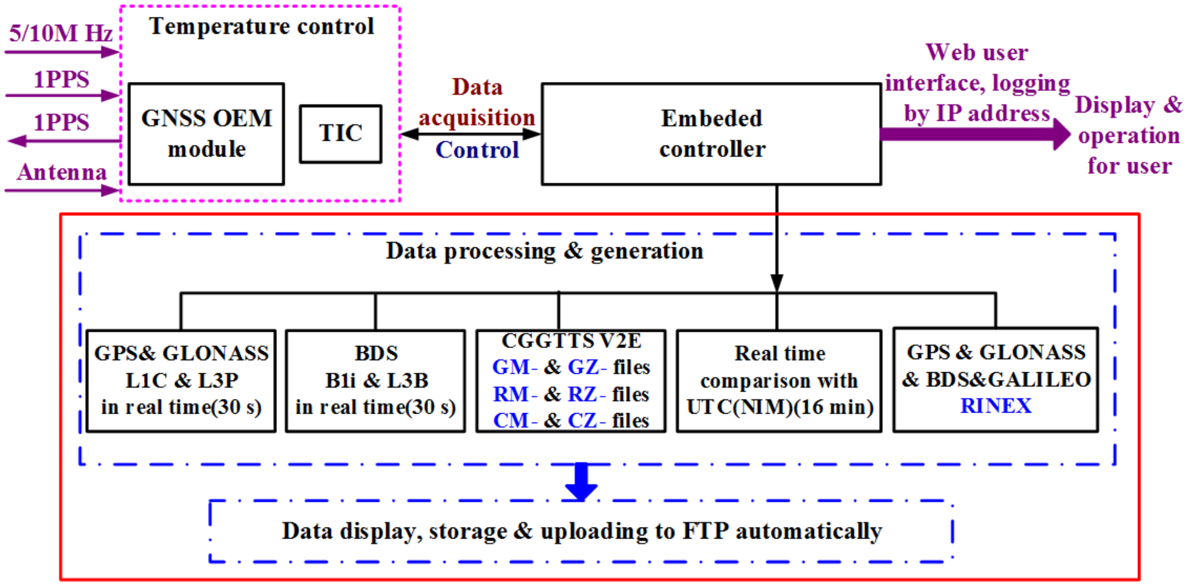

Figure 2. NIM-TF-GNSS-3 structure.

which are also slightly different from those adopted for the GPS system; the two satellite differential group delays, known as TGD1 and TGD2, which are referenced to the B3i frequency point separately for the two different frequency points B1i and B2i of BDS systems, should be taken into account (see details in [2]).

2.2. Experimental setup

The NIM-TF-GNSS-3 type of BDS time transfer receiver [9], with the capability of time and frequency transfer with GPS, GLONASS and BDS, has been under development at the NIM since 2016. Besides the NIM, several laboratories have been equipped or are planned to be equipped with NIM-TF-GNSS-3 receivers generating CGGTTS V2E (see details in [10]) and Rinex file data; these are BIPM, OP, PTB, NIST, VNIIFTRI and USNO. Also, two institutes in China have participated in experiments by operating the NIM-TF-GNSS-3 receivers, including the WIPM (Wuhan Institute of Physics and Math, Chinese Academy of Science, Wuhan) and the SIMT (Shanghai Institute of Metrology and Testing, Shanghai). The experiments in the paper actually involve seven NIM-TF-GNSS-3 receivers, which include TF06, TF07, TF09 and TF10 with reference to UTC(NIM) at the NIM, IM15 referenced to a caesium clock at the BIPM, IM16 referenced to the same caesium clock at the BIPM and at the end of July relocated to the OP and referenced to UTC(OP), TF12 with reference to a hydrogen maser at the SIMT. Settings with elevation masks of 10 or 15 degrees have been applied in all the NIM-TF-GNSS-3 receivers in subsequent experiments.

For the moment, in the experimental network, not all of the NIM-TF-GNSS-3 receivers at the various laboratories have been operated; for the global evaluation, the additional IGS tracking sites would be a good supplement to enhance the geographical distribution. All the selected sites from the IGS tracking network operate geodetic receivers synchronized or linked to external references (hydrogen masers or caesium clocks), including DAEJ (TRIMBLE NETR9) in South Korea, STR1 (SEPT POLARX5) in Australia, AGGO (SEPT POLARX4TR) in Argentina, HARB (TRIMBLE NETR9) in South Africa, YEL2 (SEPT POLARX4TR) in Canada (inside the Arctic). To implement BDS and GPS time transfer via the selected IGS tracking sites that can generally generate Rinex files only, software called RinCGG, compatible with BDS, GPS and GLONASS measurements, has been developed at the NIM to generate CGGTTS (V2E) file from Rinex data in a 30 s interval.

The major part of the analysis in the paper focuses on the code measurement results—in particular, those based on the CGGTTS data generated by the NIM-TF-GNSS-3 receivers or the RinCGG software. BDS time transfer covering different continents including Asia, Europe, North America (inside the Arctic), South America, Africa and Oceania has been evaluated.

2.3. Receiver and software tools developments

The NIM-TF-GNSS-3 receiver is operated in operation mode 1 (see operation modes in [8]). The scheme of the receiver can be divided into several parts, including one OEM GNSS module, one time interval counter (TIC), one temperature controlling system, and a processing and controlling system excluding one geodetic antenna, one surge arrester and one antenna cable as figure 2 shows. Before the receiver starts measuring, the time and frequency signals of the external time reference should be input; after starting, the GNSS module implements the raw observation together with the TIC. To fulfill the requirement of more precise carrier phase measurement investigated in [8], the temperature controlling system has been installed around the GNSS module and the TIC. The processing and controlling system is the core of the receiver for data acquisition, processing and system control, consisting of one embedded controller and one appropriate interface software. The software is network-based and can be used via a webpage logged on

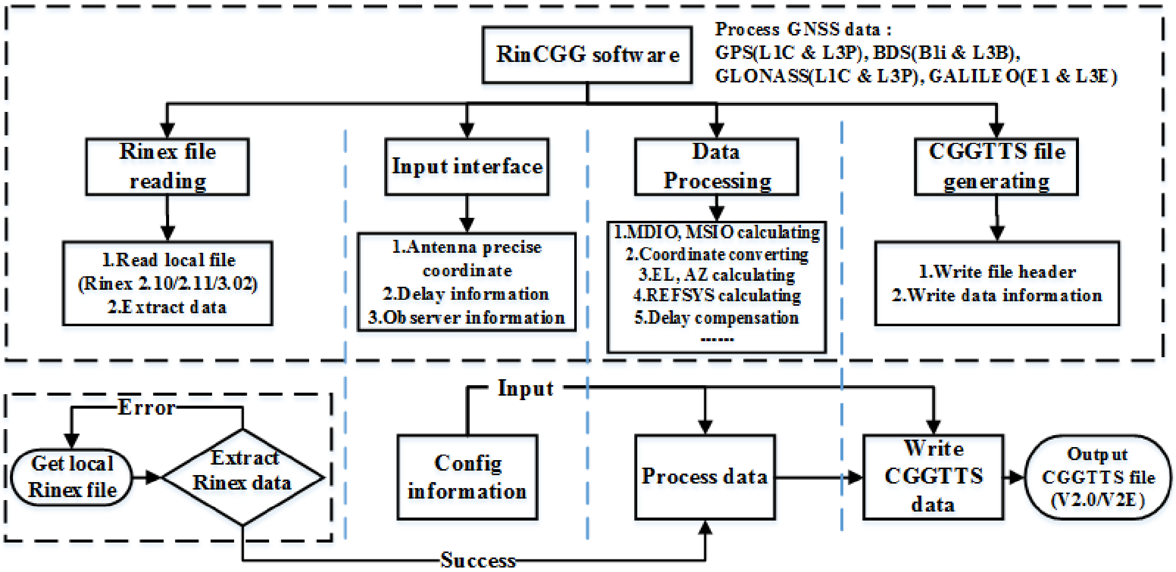

Figure 3. RinCGG structure.

through any computer with access to the receiver. Compared to its two previous versions, NIM-TF-GNSS-1 [11] and NIM-TF-GNSS-2 [12], its new features are the automatic measurement of the internal reference delay of the receiver referenced to the various time and frequency sources, the capability of performing BDS measurements and a time transfer file in accordance with CGGTTS format V2E with extended compatibility with GALILEO and BDS [10]. The receiver presently logs the CGGTTS files with the measurement types GPS C/A (L1C) and P3 (L3P) codes, BDS B1i and L3B codes, and GLONASS C1 (L1C) and P3 (L3P) codes. The GPS, BDS, GLONASS and GALILEO Rinex files including the formats of V2.10 and V3.03 are generated mainly for carrier phase time and frequency transfer. Furthermore, real-time measurement and comparison using all the measurement types in 30 s and in 16 min is realized by the software.

The RinCGG software is used to convert Rinex measurements to the CGGTTS (V2E and V2.0) file format, which is operational on the Windows 7 system for the input of GPS, BDS, GLONASS and GALILEO Rinex files (V3.02, V2.11 and V2.10). The CGGTTS files separately with GPS L1C and L3P, BDS B1i and L3B, GLONASS L1C and L3P, and GALILEO E1 and L3E measurements can be written and output. It is designed as shown in figure 3. The software consists of four main modules. The Rinex file reading module accesses a specific file and extracts the required observation data. Using this information and pre-processing input to the interface module by the user, the data processing module estimates the satellite position, the ionospheric and tropospheric delays, the range between the satellite and the receiver, the relativistic effect and the hardware delays, and acquires the final data for the CGGTTS file, such as elevation (EL), Azimuth (AZ), ionospheric delay (MDIO/MSIO), and time difference between the time reference of the receiver and GNSS system time (REFSYS). Finally, the CGGTTS generating module writes and outputs the CGGTTS files.

For our evaluation of BDS time transfer, mainly the NIM-TF-GNSS-3 receiver (generating CGGTTS (V2E) files directly) and RinCGG software (converting Rinex files to CGGTTS (V2E) files with single frequency and dual frequency measurements) were used, to achieve a more convenient construction of the evaluation network. R2CGGTTS software is not used in the final evaluation, since its present version provided in the BIPM FTP server is not updated for BDS time transfer compatibility and not capable of single frequency measurement. To verify the capacity of NIM-TF-GNSS-3 receiver and RinCGG software for BDS and GPS time transfer, CCD and long baseline experiments have been undertaken. The other types of receiver, including IM05 (Septentrio PolaRx3eTR), IM06 (Dicom GTR50, master receiver at the NIM, both referenced to UTC(NIM)), and BP0R (Septentrio PolaRx2eTR), referenced to the same caesium clock as IM15, were also involved for the sake of verification.

Figure 4 shows satisfactory results for the CCD experiments, and the data from three methods have been compared for the verification of the receiver and the software, which include CGGTTS data originally generated by the receivers TF10 and IM15, processed by RinCGG and converted by R2CGGTTS from their Rinex files. The standard deviation (std) values for all the results are below 1 ns using ten-day data, and the small deviations in TDEV curves derive from the different observation data sampling intervals (30 s for file from RinCGG and 1 s for file originally from receivers) and the different ionospheric delay compensation methods (such as dual frequency measurement for B1i files from RinCGG and modelled measurement for B1i files originally from receiver). From figures 5 and 6, even though the long-term performance is limited by Cs clock parameters, we can evaluate the agreement between the various methods via remote comparison and observe that the mean value and the std for the double differences of the results between those generated either by receiver or by RinCGG and those generated by R2CGGTTS are below 0.3 ns and 0.4 ns respectively. Generally, the receiver and the software are competent for the evaluation of BDS time transfer in comparison to GPS.

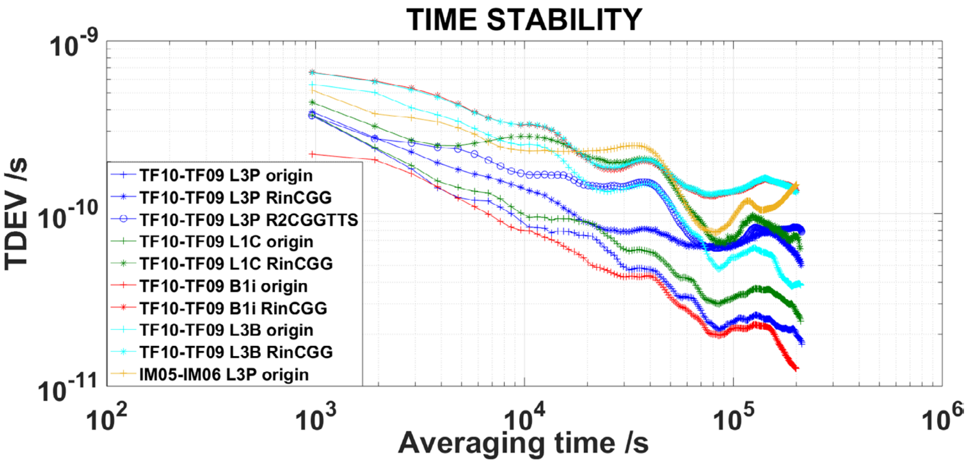

Figure 4. Time Deviation (TDEV) of time difference using CCD for NIM-TF-GNSS-3 and RinCGG verification; L3P: GPS L3P measurement; L1C: GPS L1C measurement; B1i: BDS B1i measurement; L3B: BDS L3B measurement; MJD: Modified Julian Date.

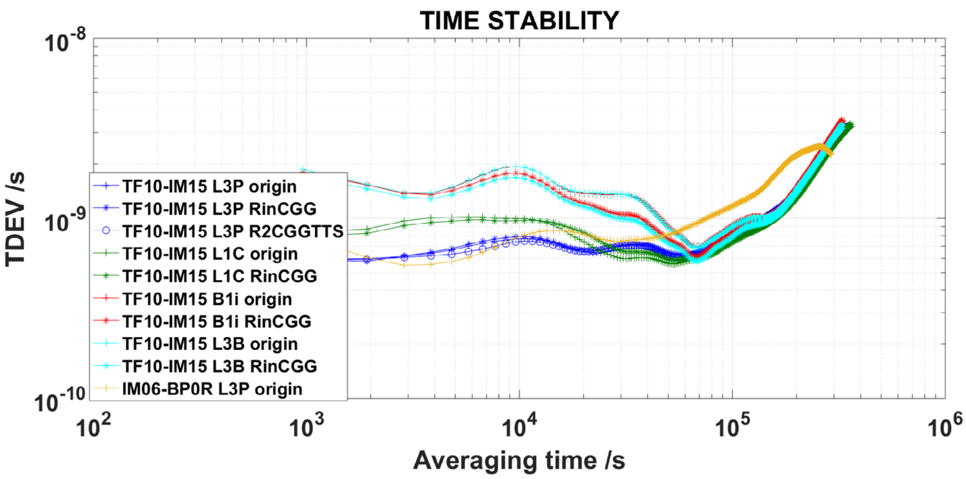

Figure 5. TDEV of time difference using remote comparison for NIM-TF-GNSS-3 and RinCGG verification.

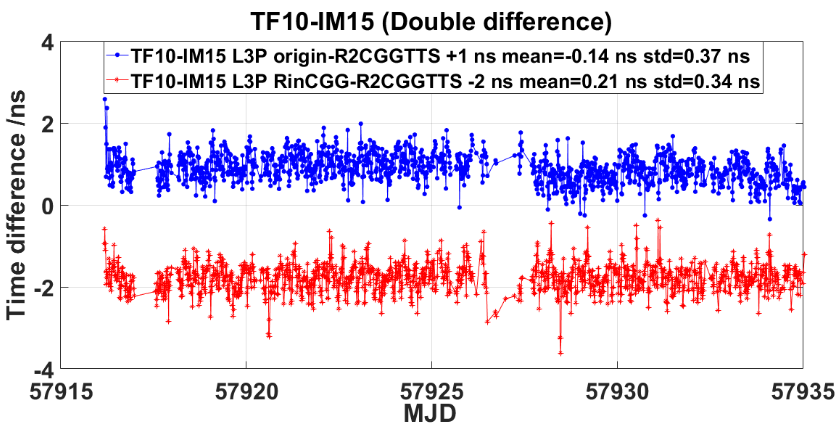

Figure 6. Double difference by remote comparison for NIM-TF-GNSS-3 and RinCGG verification; Blue: double difference of TF10-IM15 between the CGGTTS data originally from the NIM-TF-GNSS-3 receivers and the CGGTTS data converted by R2CGGTTS; Red: double difference of TF10-IM15 between the CGGTTS data converted by RinCGG and by R2CGGTTS.

3. Satellite signal coverage statistics

The space segment of the BDS system involves satellites of three types : GEO, IGSO and MEO. The GEO and IGSO satellites, with a one-day cycle around the Earth, are more than 36 000 km away from the receivers, and the MEO satellites, which have return cycles of 7 d with 13 orbits around the Earth, are more than 20 000 km away from the receivers. The GEO satellites assisted in measurements in the Asia–Pacific region during the first phase of BDS constellation construction. However, the global satellite network of BDS system is not yet complete; due to the limited coverage area for GEO

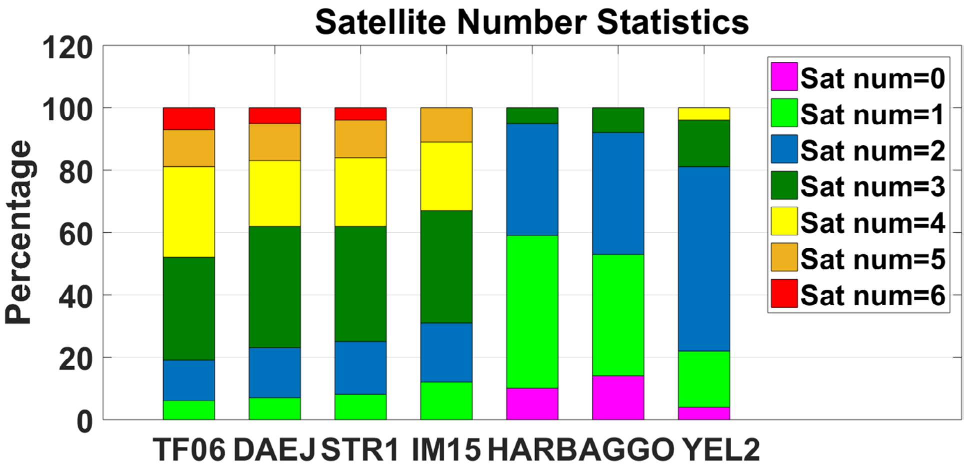

Figure 7. Satellite number statistics.

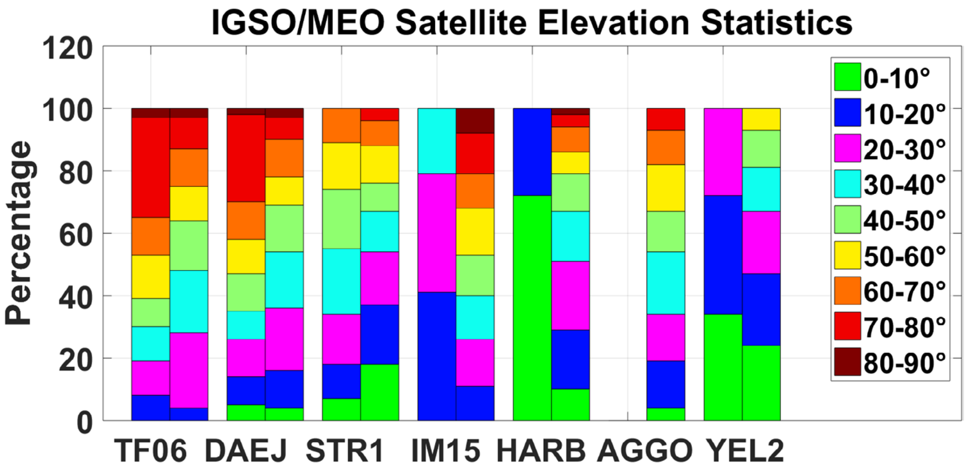

Figure 8. Elevation statistics of BDS IGSO/MEO satellites.

satellites, in the present constellation only the IGSO and MEO satellites will be focused on for further investigation and implementation of BDS time and frequency transfer.

The observability of BDS satellites was a criterion in the selection of sites on several continents for the statistics on satellite signal coverage presented in figures 7 and 8. From the results shown in figure 7, at the sites in Asia, Oceania and Europe, excluding GEO satellites, three or four satellites should be in view for around 80% of the time, and in Asia and Oceania there is a more dense coverage from GEO satellites, which may lead to significant advantages in time transfer. At the sites in Africa, South and North Americas, the percentage for one or two satellites is about 80%, and the chance of no satellite being observable is less than 20%.

From figure 8, for satellite elevation, the statistics at TF06 and DAEJ in Asia, IM15 in Europe and AGGO in South America are seen to be a little better than those at the other sites; anyway, MEO satellites were in general found to have more similar coverage at the various sites in different continents. While IGSO has a much higher elevation at the sites in Asia and Oceania, especially in Asia, the situation at the sites in Europe, Africa, and the Americas is less satisfactory, especially at AGGO in South America, where no IGSO satellites were received. For time and frequency transfer, one satellite is the lowest limit, allowing time and frequency transfer solutions for most of the time, as presented in figure 7.

In order to compare the signal coverage difference between BDS and GPS in more detail, taking IM15 at the BIPM and TF06 at the NIM as instances, figure 9 shows the satellite visibility with elevation and azimuth of IM15 at the BIPM (on the left) and TF06 at the NIM (on the right), based on fourteen-day observation cover two return periods of BDS MEO satellites. For the MEO satellite, similar statistics were obtained from IM15 and TF06; for the IGSO satellite, TF06 has much better visibility considering elevation and azimuth. For GPS, there are only MEO satellites for the civil service; thus, in figure 9, a similar good coverage is observed from IM15 and TF06. The antenna location of IM15 at the BIPM is just beside a small hill roughly in the west and northwest direction, which blocks the west and north-west view of the receiver with a natural high elevation mask of about 30 degrees. This effect is visible from the azimuth of the satellites received by the IM15 receiver depicted in figure 9.

However, from figure 10, it can be seen that the number of BDS satellites in view at the BIPM position is in general two or three, which is not fully adapted to the construction of good dilution of precision and continuous positioning. At TF06, there are considerably more satellites when counting

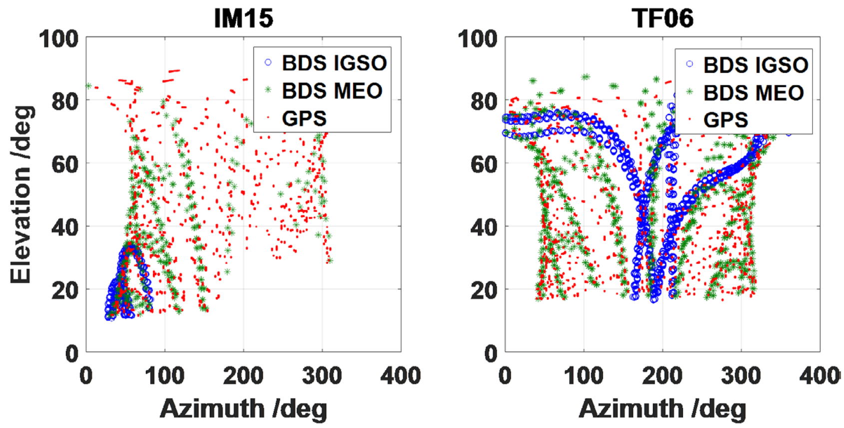

Figure 9. Elevation and azimuth for IM15 (at the BIPM) and TF06 (at the NIM).

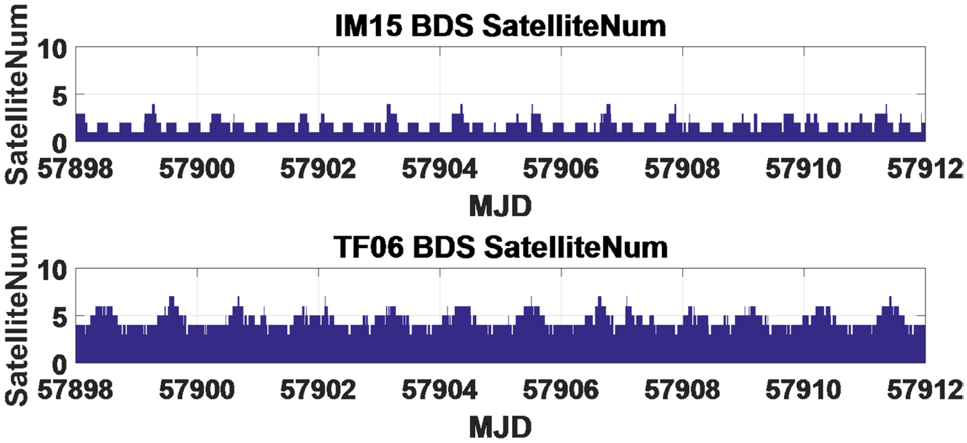

Figure 10. BDS satellite number statistics of IM15 (at the BIPM) and TF06 (at the NIM).

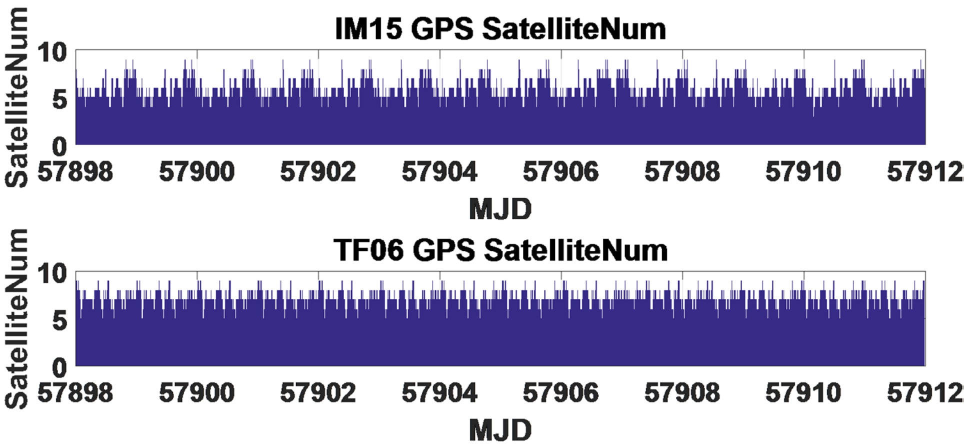

Figure 11. GPS satellite number statistics of IM15 (at the BIPM) and TF06 (at the NIM).

the number of GEO satellites, which generates the better signal coverage and also the BDS measurement in the Asia–Pacific region. For comparison, figure 11 shows the number of satellites in view from the GPS constellation in Beijing and Paris, where from a total of more than 30 MEO satellites in most cases nine or ten are visible. Considering the position and the surroundings of the receivers at the BIPM antenna position, the number of satellites in view for either GPS or BDS is fewer than those in open and wide areas without any obstacles, and also at the NIM.

4. Stability and accuracy

The time and frequency transfer experiments have been performed over long baselines, especially multiple inter-continental baselines from the several hundred kilometres to nearly 20 000 km. Stability (also including the measurement noise level) is evaluated using CCD experiments at various locations including Beijing and Paris, and long baseline experiments. Accuracy is mainly judged from the long baseline time transfer results after time link calibration.

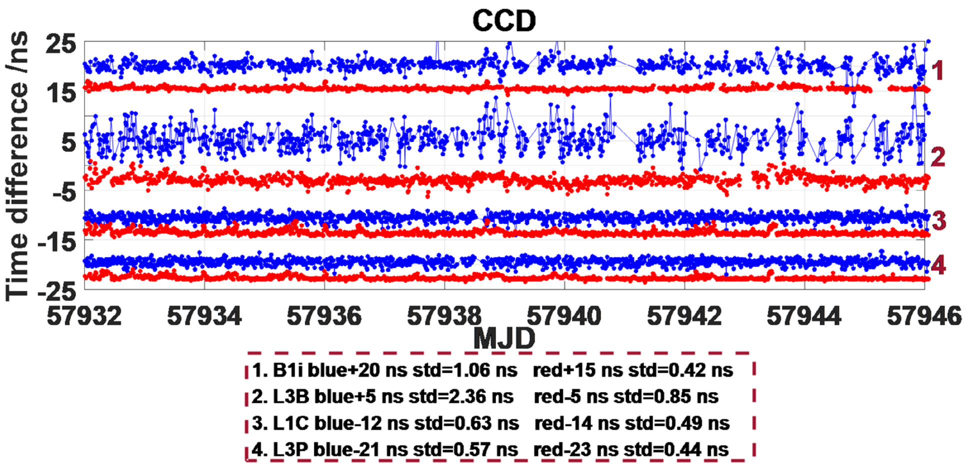

Figure 12. Time differences of BDS and GPS CCD experiments between IM15 and IM16 at the BIPM (blue), TF06 and TF07 at the NIM (red).

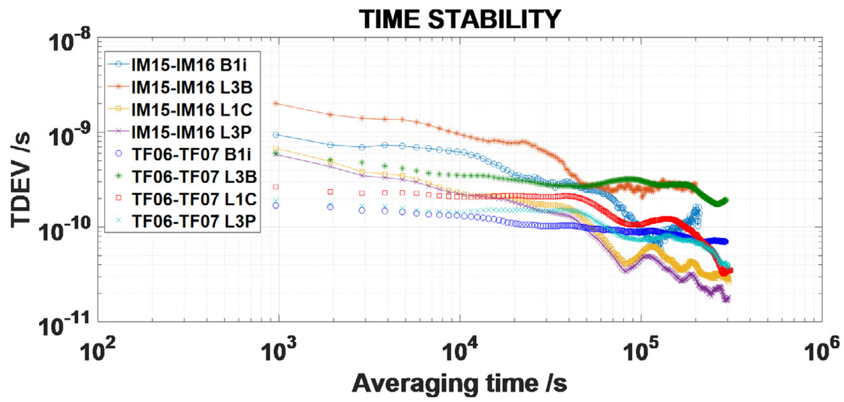

Figure 13. TDEV for the time differences of BDS and GPS CCD experiments between IM15 and IM16 at the BIPM, TF06 and TF07 at the NIM.

4.1. CCD experiments at different sites

The stds of the results in the CCD experiments are used for measurement noise level estimation. The CCD experiment is also one basic method for the judgement of short-term instability, since the short-term results in GNSS remote comparison are affected by other factors such as the operational conditions at the location (such as multi-path effect), satellite signal reception at the location and so on, besides the time transfer link constructed by the time transfer equipment.

From figure 12, at the BIPM position, a std of about 1 ns has been obtained through the CCD results of BDS B1i code using the two new GNSS receivers of the same type (NIM-TF-GNSS-3) and less than 3 ns std can be obtained using the BDS L3B code, which is consistent with what is expected in terms of the law of propagation of the uncertainty [13]. To decrease the influence of poor satellite coverage on the evaluation of the receiver performance, CCD experiments with the two NIM-TF-GNSS-3 receivers at the NIM have been implemented as well. It is shown that the receivers in Beijing are affected by a lower measurement noise level, since there is better satellite coverage at the NIM. Judged from the std in figure 12 and TDEV in figure 13, at the BIPM position, the measurement noise level for the time transfer results by BDS is worse than that at the NIM position, due to the poorer satellite signal coverage. However, for BDS B1i code measurements, there is a measurement noise level of about 1 ns, which is comparable and close to that of the GPS results, and there is a time stability of less than 1 ns over the averaging time of several thousand seconds. The B1i code of BDS has a slightly better noise level than the L1C code of GPS at the NIM, maybe due to its having double the bandwidth of the GPS C/A signal.

4.2. Comparison among the different links on long baselines

The experiments on long baselines, especially the inter-continental baselines, are designed to be implemented for the validation of the long-term stability and accuracy of BDS time transfer. Taking the example of the common view of TF06 and IM15, on the Asia–Europe baseline, figure 14 shows that, for BDS, the number of satellites in each 16 min measurement interval in common view is two for most of the time, compared to three for GPS, because of the very long baseline length. But much fewer BDS satellites are visible for IM15 than those for TF06 (as shown in figures 10 and 11), and this imbalance in two stations will mean that all-in-view (AV) mode may not manifest its full advantages, especially with the broadcast ephemeris. In the case of GPS, with the greater

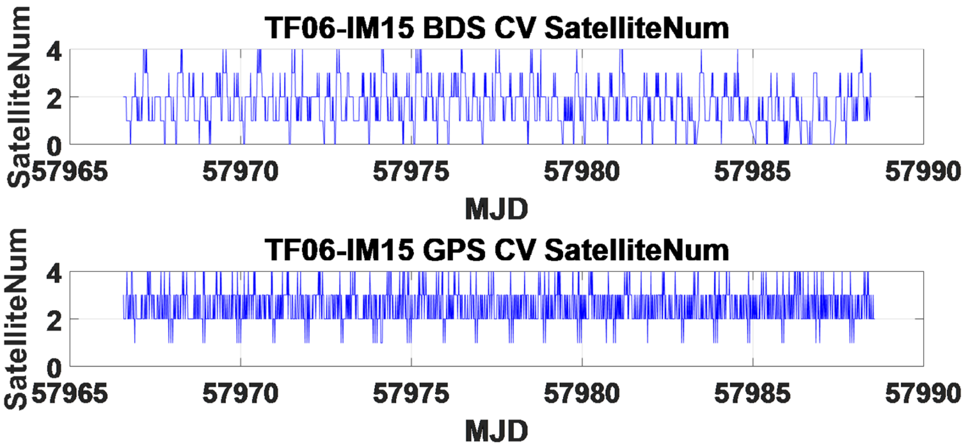

Figure 14. Satellite numbers in CV between IM15 (at the BIPM) and TF06 (at the NIM) for BDS and GPS.

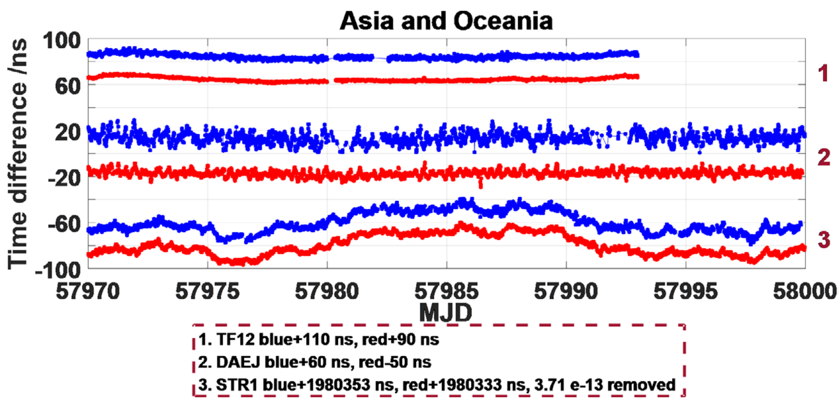

Figure 15. Time differences by BDS (blue) and GPS (red) between TF06 and the receivers in Asia and Oceania.

number of satellites at both locations in balance—generally more than seven satellites in this case—the AV mode should be more advantageous [14]. In the standard BIPM AV procedure for GPS, the precise ephemeris is used because of some qualitative reasons, such as better satellite clock and position estimation than the broadcast navigation message. The BDS case should be similar, and the precise BDS ephemeris from MGEX would be used after the quantitative evaluation of the ephemeris and its application in BDS AV time transfer. To date, however, all the comparison results over long baselines have been obtained through differentiation between two receivers after averaging the measurements of all satellites at the same epoch for each receiver in AV mode with the broadcast navigation message.

The receivers with caesium clock references were selected so that the consistency between GPS time transfer and BDS time transfer is more easily and clearly observed for B1i and L3B code measurements. The results of the receivers with hydrogen maser references are removed by a single large frequency offset marked inside the figures.

All the comparisons on the inter-continental baselines are referenced to TF06 as the pivot receiver at the NIM. Since the sites are distributed in various regions, giving rise to diverse time transfer performances according to the satellite coverage statistics, the sites involved in the experiment have been divided into three groups: 1. Asia and Oceania, 2. Africa and Americas, and 3. Europe. However, DAEJ and HARB use TRIMBLE NETR9 receivers that are not specifically designed for time transfer, and one site (YEL2) is inside the Arctic.

From the time difference results in figures 15 and 16, some gaps can be seen as a consequence of missing raw observation data—mainly due to the receiver—such as TF12, DAEJ and HARB, which may be the main source of the deviation of TDEV between BDS and GPS time transfer in figures 17 and 18. In particular, some turbulence is observed at DAEJ for an unknown reason. The TDEV results from the links with the various IGS sites are not so close at short-term, maybe due to the receiver not being specifically designed for time transfer—which may bring more uncertainty to the analysis—and different operational conditions, as described in the previous paragraph. However, there is good agreement on the long-term comparison between the BDS and GPS results between TF06 and the sites in Asia, Oceania, Africa and the Americas.

More than 270 d data between MJD 57780 and MJD 58058 have been used in the comparison over the BIPM–NIM baseline presented in figure 19. Results obtained with BDS and GPS with the pair of NIM-TF-GNSS-3 receivers are in good agreement. It was possible to assess the capacity and reliability for long time operation on this baseline. There are measurements for around 90% of the time. However, the small degradation in TDEV in figure 20 between the results of BDS and GPS could derive from the missing data due to the poor satellite coverage.

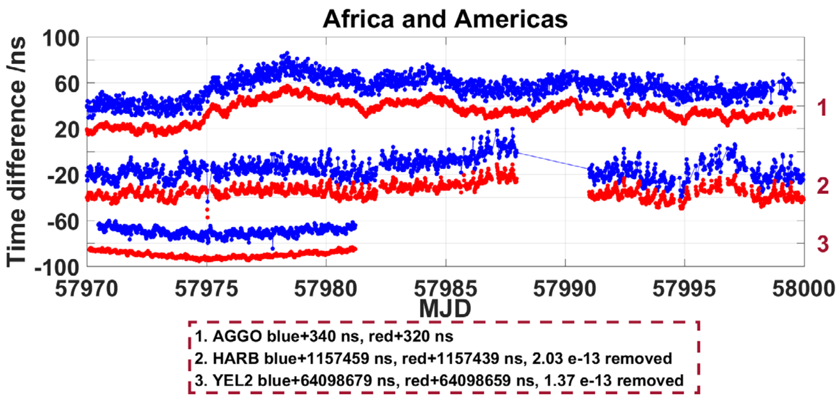

Figure 16. Time differences by BDS (blue) and GPS (red) between TF06 (at the NIM) and the receivers in Africa and Americas.

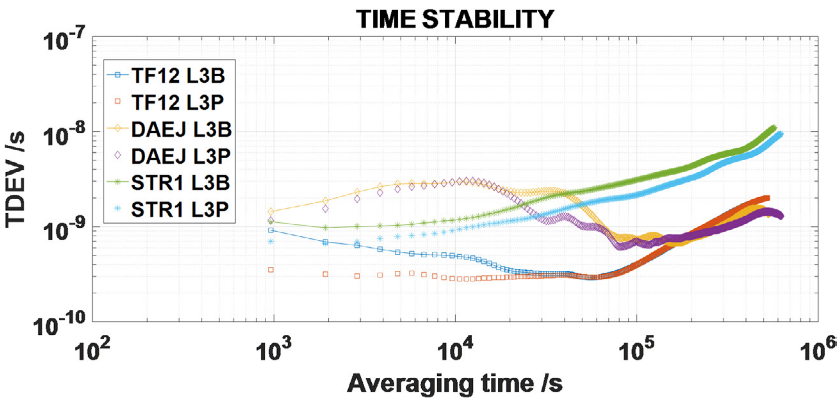

Figure 17. TDEV for the time differences by BDS and GPS between TF06 (at the NIM) and the receivers in Asia and Oceania.

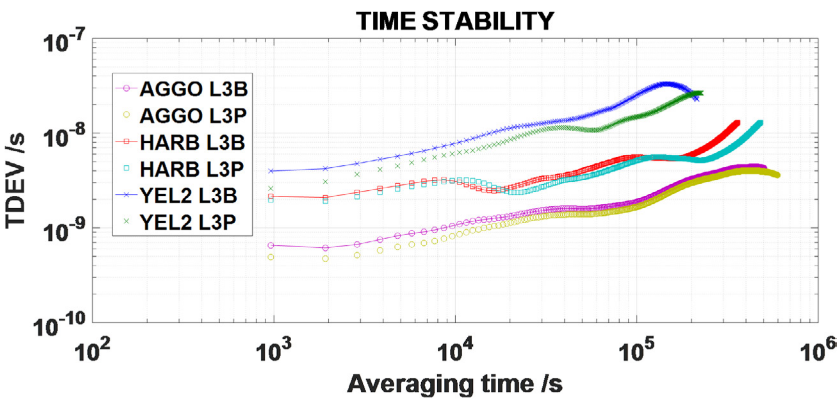

Figure 18. TDEV for the time differences by BDS and GPS between TF06 (at the NIM) and the receivers in Africa and Americas.

Additionally, the experiments have been implemented separately over the BIPM–TP (Institute of Photonics and Electronics, Czech Academy of Sciences (IPE/ASCR), Prague, Czech Republic—one laboratory contributing to UTC) link inside Europe, as shown in figures 21 and 22.

At the TP, there are one time and frequency transfer receiver (TP01, Dicom GTR55) compatible with GPS and BDS, and one time and frequency transfer receiver (TP04, Dicom GTR50) with GPS measurements, for mutual comparison and verification. TP is about 1000 km distant from the BIPM, and the time transfer was implemented using CV mode.

Through IM15 and TP receivers, approximate consistency can be observed between the results of BDS and GPS time transfer on IM15–TP baselines in figure 21. TDEV shows agreement at long-term in figure 22. On IM15–TP baselines, there are some obvious BDS observation gaps due to less time for observable satellites; this poor coverage makes the time difference by BDS on IM15–TP baselines look noisier, and is responsible for the short-term deviation of TDEV and also the smaller deviation of TDEV over long averaging time between BDS and GPS.

Time link calibration should be implemented for the accurate evaluation of time transfer. Since no receiver has been calibrated absolutely on BDS signals, the BDS calibration for this target has been implemented by calibrating all BDS time links by CCD experiments between the receivers of the link. All the BDS links involved between the pivot receiver TF06 and the other receivers were calibrated. For the GPS

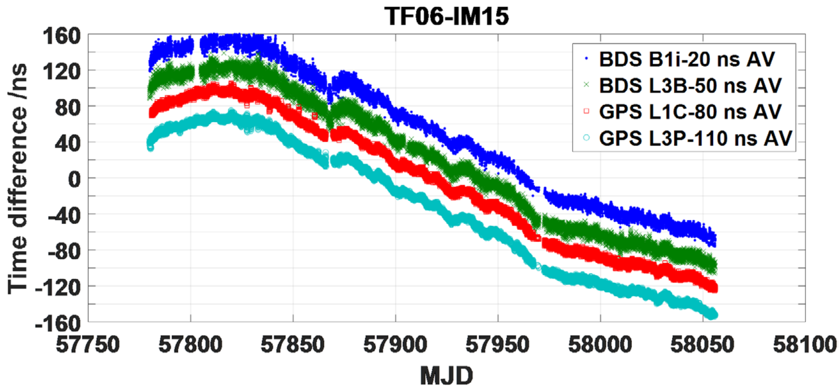

Figure 19. Time differences by BDS and GPS between TF06 (at the NIM) and IM15 (at the BIPM).

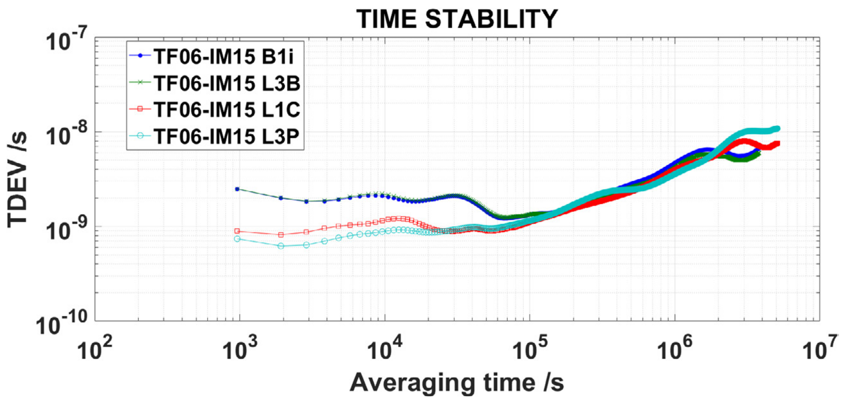

Figure 20. TDEV of the time differences by BDS and GPS between TF06 (at the NIM) and IM15 (at the BIPM).

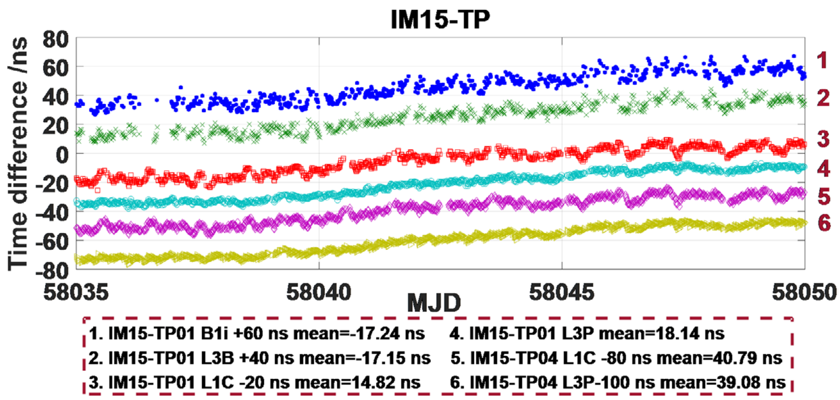

Figure 21. Time differences between IM15 (at the BIPM) and TP receivers.

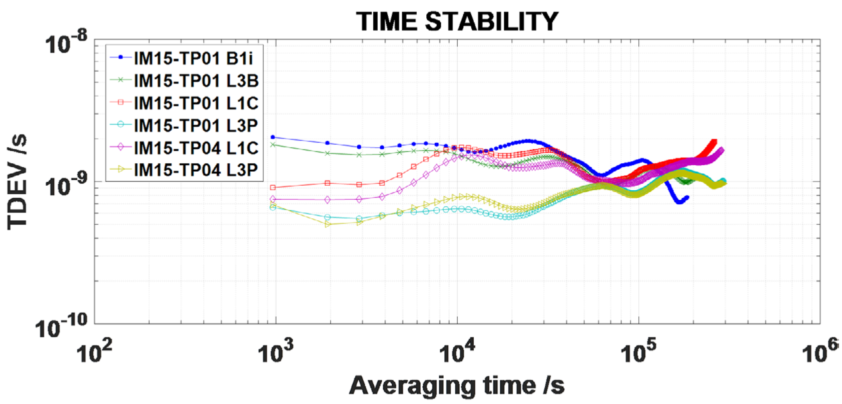

Figure 22. TDEV of the time differences between IM15 (at the BIPM) and TP receivers.

Table 1. Calibration values for BDS links with reference to TF06 and GPS receivers.

Site	B1i (with TF06) /ns	L3B (with TF06) /ns	L1C /ns	L3P /ns
IM15	−3.2	4.9	−7.1	−10.9
IM16	−3.3	4.8	−5.1	−8.9
TF06			−12.4	−16.1
TF07	0.3	6.2	−3.8	−6.9
TF09	0.2	9.9	−4.9	−8.4
TF10	−0.6	7.4	−4.7	−7.9
TF12	−2.8	3.9	−6.2	−9.7
IM05			74.0	62.1
IM06			−30.4	−31.3

Table 2. Time transfer results for the NIM-BIPM baseline experiments.

Site pair	B1i /ns	L3B /ns	L1C /ns	L3P /ns
IM06–BP0R				47.7
IM06–BP0T				48.1
IM06–BP1B				47.0
IM06–BP1J				47.2
TF06–IM15	45.4	45.9	46.2	45.7

time link calibration, one calibration value for each receiver (TF06 included) individually has been acquired by differential calibration referenced to IM06 calibrated by the BIPM. The calibration values for both BDS links and GPS receivers are presented in table 1. Using CCD methods for BDS link calibration, similar to differential calibration of the GPS receiver method with closures (see details in [15]), the combined uncertainty for the calibration is estimated as less than 3 ns, and the uncertainty for GPS link calibration is also estimated as less than 3 ns.

In addition, during the experiments on the BIPM–NIM link, the BDS calibration was compared and verified using the calibrated GPS time transfer results. Finally, with the data used between MJD 57860 and MJD 58032, the averages of the time transfer results at all epochs were computed, and are presented in table 2. BIPM receivers BP0R (reference receiver for TAI calibration), BP0T (Dicom GTR50), BP1B (Piktime TTS4) and BP1J (Septentrio PolaRx4TRpro), all referenced to the same caesium clock as IM15, have been used for the verification. The results obtained by both GPS and BDS over the long baseline NIM–BIPM with the references of UTC(NIM) and one caesium clock respectively agree within 2.7 ns, even though there were incomplete data in some epochs because of some data gaps. BP0R is the reference receiver for the other BIPM receivers, and the time transfer results between IM06–BP0R and TF06–IM15 receiver pairs are consistent within 2.3 ns. However, the obvious missing data in the TF06–IM15 link might impede better consistency.

5. Summary and expectation

A new time and frequency transfer system (NIM-TF-GNSS-3) capable of using the signals from BDS and other GNSS constellations, and a new software application (RinCGG) converting to CGGTTS (V2E) file from Rinex file, have been developed at the NIM. The types of receiver have been selected for the first time transfer by BDS over the Asia–Europe baselines, and a number of significant laboratories in the UTC network and other institutes in China are or will be equipped with such receivers for the full evaluation of BDS time transfer towards UTC contribution. One Czech site and some IGS tracking sites with RinCGG generating CGGTTS data have also been involved for this first evaluation. The satellite signal coverage statistics for six continents (Asia, Oceania, Africa, South and North Americas, and Europe) were studied; considering the satellite number, elevation and azimuth, we conclude that they are adequate for time transfer across these continents. For BDS time transfer, by CCD experiments, the measurement noise level of about 1 ns and the short-term instability with the NIM-TF-GNSS-3 receivers have been evaluated as comparable to those of GPS time transfer, opening up the possibility of using BDS time and frequency transfer over long baselines. Through experiments over long baselines, especially inter-continental baselines, for the estimation of stability at long-term and of accuracy, the results show agreement between BDS and GPS time transfer results in view of the satellite coverage. With the time transfer link calibration, the accuracy of the time transfer by BDS has been also characterized, and the difference from the GPS results is within 2.7 ns. In principle, these studies conclude the feasibility of BDS time transfer over inter-continental baselines and that this can be considered as a viable method for time transfer towards UTC contribution.

The next steps will include all the available data from the UTC participating laboratories in an experimental network and implement the comparison of the links obtained with multiple techniques, such as TWSTFT (Two Way Satellite Time and Frequency Transfer) and GPS PPP (Precise Point Position), and some discussion about the involvement of the precise ephemeris and AV, which is closer to the implementation in UTC computation. Additionally, to relate UTC and TAI with predictions of UTC(k) disseminated by BDS, BDT monitoring methodology and data generation, together with absolute calibration of BDS time transfer receivers, will be studied.

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