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

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Abstract. The road map for the implementation of BeiDou Navigation Satellite System (BDS) time transfer in Coordinated Universal Time (UTC) has been drawn up, including the pilot experiment to evaluate BDS time transfer on multiple baselines. In the pilot experiment, several laboratories contributing to UTC have been equipped or planned to be equipped with the 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 the multiple inter-continental baselines, involving NIM, BIPM, other institutes in China and Czech, and stations from the International Global Navigation Satellite System (GNSS) Service (IGS) network. The satellite signal coverages at different sites were characterized for satellite number, satellite elevation and satellite azimuth. Stability and accuracy of time transfer by BDS have been evaluated, based on the Common Clock Difference (CCD) and the multiple inter-continental baselines experiments, concluding the 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.

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1. Introduction

To date, totally 31 navigation satellites have been launched in the BeiDou Navigation Satellite System (BDS) system 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 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) 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 until 2020, and after that 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) [1] in BDS-2 system has been published for the formal use.

Research on time and frequency transfer using BDS has progressed particularly in recent years. In 2013 [2], code-based and carrier phase BDS time transfer were introduced using a prototype receiver, which was based on one OEM (Original Equipment Manufacturer) module; the receiver without calibration was synchronized with an external reference, and Common Clock Difference (CCD) and short baseline experiments have been implemented and evaluated. In 2014 [3], a frequency transfer method using the carrier phase solutions of only 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) [4]. In 2016 [5], 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) [6] establishes as one target the development of a multi-constellation clock comparison. This, combined with the rapid development of BDS, has prompted the studies on BDS time transfer among different 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 in the global scale, rises to the surface.

A new multi-GNSS version of time transfer system, NIM-TF-GNSS-3, has been developed at the NIM. Finished in the mid 2016, it is capable of time and frequency transfer with GPS, GLONASS (GLObal NAvigation Satellite System) and BDS. Two of these new systems were installed at the BIPM in 2017 as part of the pilot experiment originally planned to investigate the time transfer performance with 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 have a good geographical distribution. These institutes will operate the receivers provided by the NIM. One software called RinCGG was developed to generate CGGTTS (V2E) file from Rinex file 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 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 the time comparison over multiple inter-continental baselines. At present, NIM-TF-GNSS-3 receivers have been operated at the NIM, the BIPM, the OP and the PTB. More data will be incorporated in several months from the other participants. In the paper, the BIPM, the NIM, one Chinese institute operating one NIM-made receiver, one Czech institute and a few tracking sites of the International GNSS Service (IGS) have been involved in this first evaluation.

2. IMPLEMENTATION OF BDS TIME TRANSFER

2.1. Principles

At present there are fourteen satellites including five GEO, six IGSO and three MEO satellites [7] for use in positioning, navigation and timing. The time reference for the BDS is the BDS Time (BDT), which adopts the international system of units (SI) 'second' as the basic unit for the continuous accumulation, without inserting leap seconds. The start epoch of BDT is 00:00:00 on 1 January 2006 of UTC. BDT offset with respect to UTC is maintained within 100 ns (modulo 1 second). The leap seconds are broadcast in a navigation message [1]. Thus, the difference between International Atomic Time (TAI) and BDT is within 100 ns plus a constant 33 seconds, while the integral number difference of seconds between BDT and UTC is 4 since 1 January 2017 and until the next insertion of a leap second.

Presently, time and frequency transfer by BDS could be through mainly three types of signals that are 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 in the two stations [2]. The reference

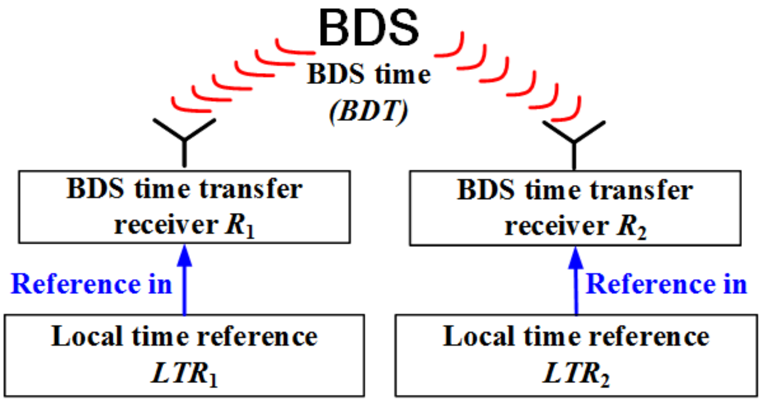

Figure 1. Time and frequency transfer by BDS

methods can 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 equation (1)-(3).

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

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

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

In time transfer by BDS, some parameters related to the earth reference frame are worth mentioning. These are the earth's gravitational constant and the earth's rotation rate, 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 B3 frequency point separately for the two different frequency points B1i and B2i of BDS systems should be taken into account (see details in [1]).

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 the NIM-TF-GNSS-3 receivers generating CGGTTS V2E and Rinex files data, which are BIPM, OP, PTB, NIST, VNIIFTRI, USNO. Also, two institutes in China have participated in the 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 involves 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. The settings with elevation masks of 10 or 15 degrees have been applied in all the NIM-TF-GNSS-3 receivers in the further experiments.

For the time, in the experimental network, the NIM-TF-GNSS-3 receivers haven't been operated at all the laboratories, and for the global evaluation the additional IGS tracking sites would be a good supplement in geographical distribution. All the selected sites from the IGS tracking network are operating the geodetic receivers synchronized or linked to the 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, one software called RinCGG compatible with BDS, GPS and GLONASS measurements is 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, particularly 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 with the operation mode 1 (see operation modes in [8]). The scheme of the receiver can be divided into several parts, including one GNSS OEM module, one time interval counter (TIC), one temperature controlling system, and the 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 and after starting 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 controlling, which consists of one embeded controller and one interface software. The software is network-based and can be used by the webpage logged on through any computer that can be accessed to the receiver. Compared to its two previous versions NIM-TF-GNSS-1 [10] and NIM-TF-GNSS-2 [11], its new features are the automatic measurement of the internal reference delay of the receiver referenced to the different time and frequency sources, the capability of BDS measurements and the time transfer file in accordance with CGGTTS format V2E with the extended compatibility with GALILEO and BDS [12]. The receiver presently logs

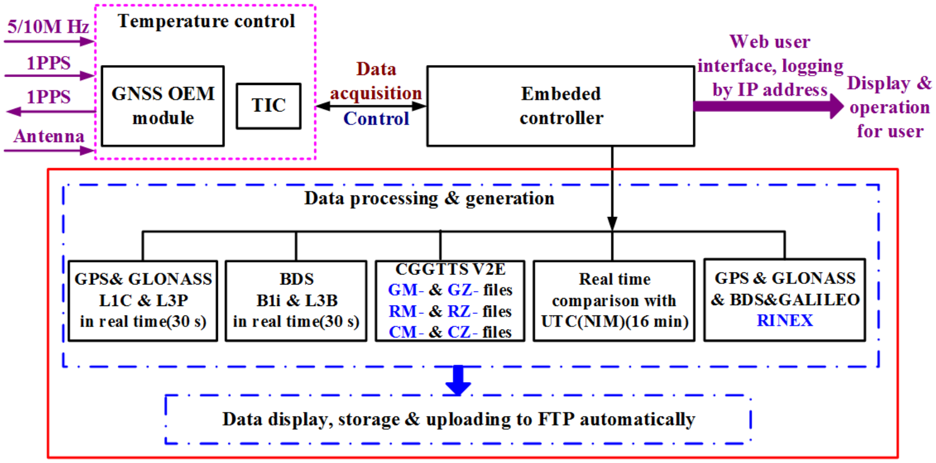

Figure 2. NIM-TF-GNSS-3 structure

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 for mainly carrier phase time and frequency transfer. Furthermore the real time measuring and comparison using all the measurement types in 30 seconds and in 16 minutes is realized by the software.

The RinCGG software is used to convert Rinex measurements to CGGTTS (V2E and V2.0) file, which is operational on the Window 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 could be written and output. It is designed as Figure 3 shows. The software consists of four main modules. The Rinex file reading module is for getting the specific file and extracting the required observation data. By the information and pre-processing from input interface module by the user, data processing module estimates the satellite position, ionospheric and tropospheric delays, the range between the satellite and the receiver, relativistic effect and hardware delays, and get the final data in CGGTTS file, such as elevation (EL), Azimuth (AZ), inospheric delay (MDIO/MSIO), time difference between the time reference of the receiver and GNSS system time (REFSYS). Finally CGGTTS generating module writes and outputs the CGGTTS files.

For this evaluation of BDS time transfer in the paper, mainly the NIM-TF-GNSS-3 receiver generating CGGTTS (V2E) file directly and RinCGG software converting Rinex file to CGGTTS (V2E) file with single frequency and dual frequency measurements were used for more convenient construction of 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 the single frequency measurement. To verify the ability of NIM-TF-GNSS-3 receiver and RinCGG

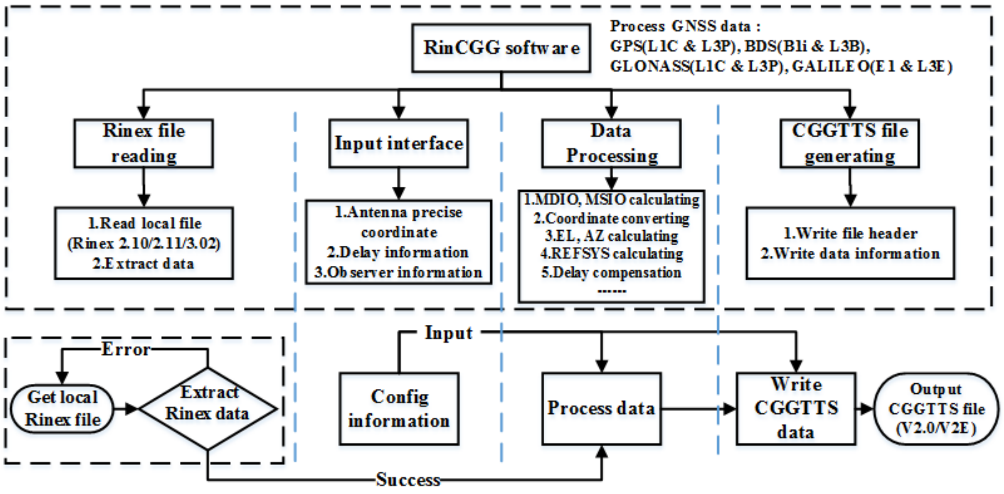

Figure 3. RinCGG structure

software for BDS and GPS time transfer, the experiments of CCD and long baseline have been done. The other types of receivers including IM05 (Septentrio PolaRx3eTR), IM06 (Dicom GTR50, master receiver at NIM, both referenced to UTC(NIM)) and BP0R (Septentrio PolaRx2eTR) referenced to the same Caesium clock as IM15 also were involved for the verification.

From Figure 4, there is quite good result 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, converted 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. From Figure 5 - 7, the agreement among the methods can be got from remote comparison and the mean value and the std for the double differences of the results between either generated by receiver or by RinCGG referenced and the ones by R2CGGTTS are below 0.3 ns and 0.4 ns separately. Generally, the receiver and the software is able to be competent for the evaluation of BDS time transfer compared to GPS.

3. SATELLITE SIGNAL COVERAGE STATISTICS

The space segment of the BDS system involves three types of satellites, GEO, IGSO and MEO satellites. The GEO and IGSO satellites with a one-day cycle around the earth are more than 36000 kilometres from the receivers, and the MEO satellites, which have the return cycles of 7 days with 13 orbits around the earth, are more than 20000 kilometres 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 accomplished; due to the limited area for GEO 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.

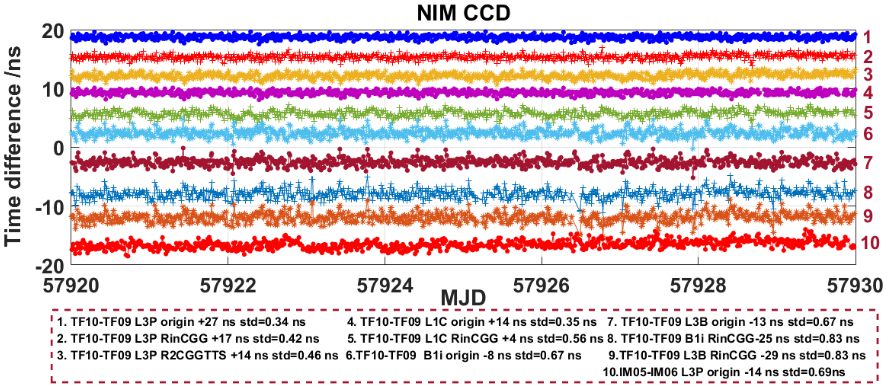

Figure 4. Time difference using CCD for NIM-TF-GNSS-3 and RinCGG verification; L3P: GPS L3P measurement; L1C: GPS L1C measurement; B1i: BDS B1i measurement; L3B: BDS L3B measurement; MJD: Modified Julian Date

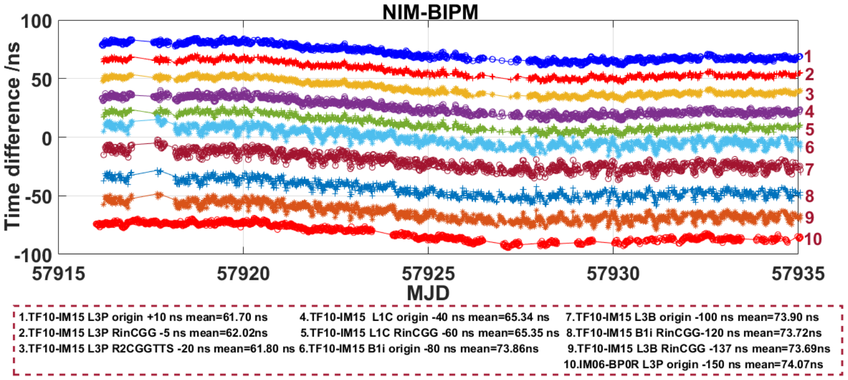

Figure 5. Time difference using remote comparison for NIM-TF-GNSS-3 and RinCGG verification

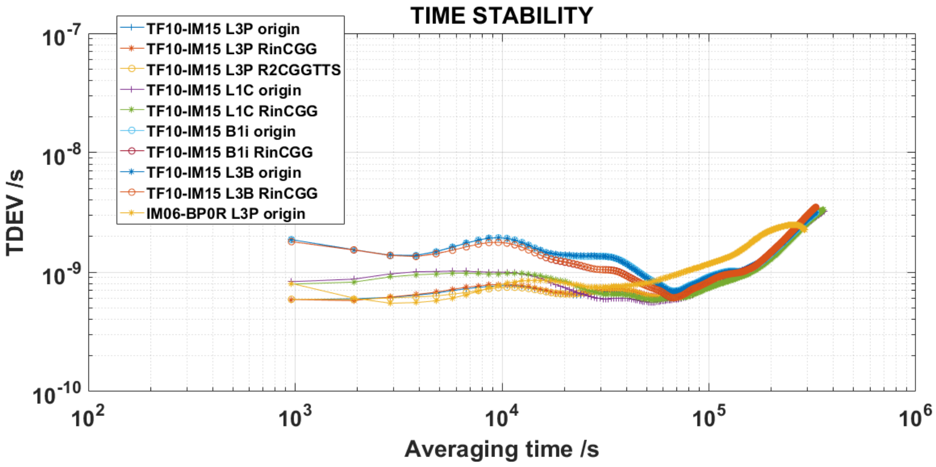

Figure 6. Time Deviation (TDEV) of time difference using remote comparison for NIM-TF-GNSS-3 and RinCGG verification

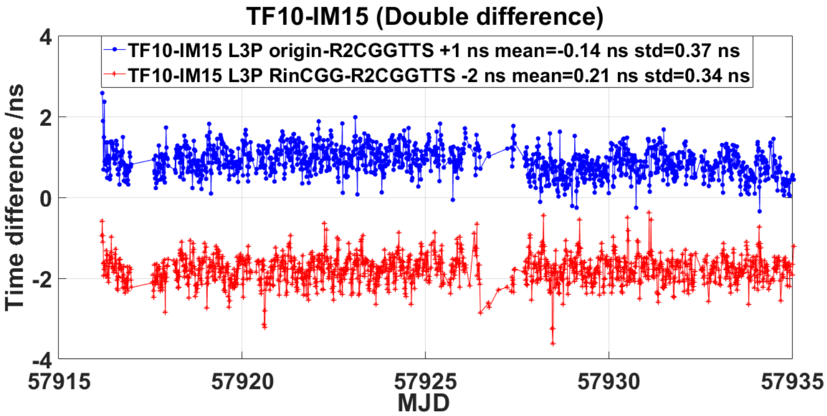

Figure 7. Double difference by remote comparison for NIM-TF-GNSS-3 and RinCGG verification; Blue: double difference of TF10-IM15 between the CGGTTS data originally from the NIM-TF-GNSS-3 receivers and the CGGTTS data converted by R2CGGTTS; Red: double difference of TF10-IM15 between the CGGTTS data converted by RinCGG and by R2CGGTTS

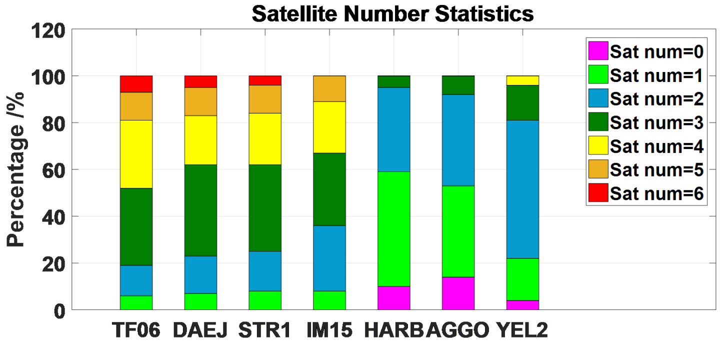

Figure 8. Satellite number statistics

The observability of BDS satellites was a criterion in the selection of sites on different continents for the statistics on satellite signal coverage presented in Figure 8 and 9. From the investigation results shown in Figure 8, 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 concentrated coverage from GEO satellites which may lead to much more advantages in time transfer. At the sites in Africa, South and North Americas, the percentage for one or two satellites is about 80% and there is a lower chance of less than 20% for having no observable satellites.

From Figure 9, for satellite elevation, the statistics at TF06 and DAEJ in Asia, IM15 in Europe and AGGO in South America are a bit better than those at the other sites, anyway, in general MEO satellites were found to have more similar coverage at the different 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,

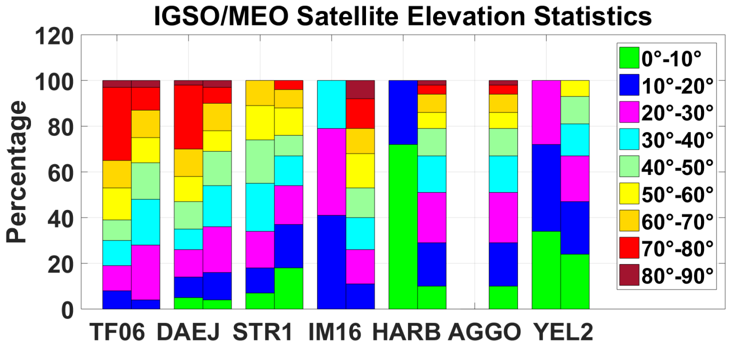

Figure 9. Elevation statistics of BDS IGSO/MEO satellites

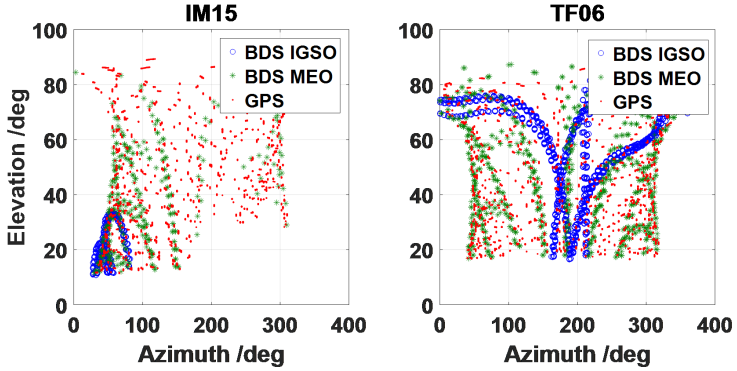

Figure 10. Elevation and azimuth for IM15 (at the BIPM) and TF06 (at the NIM)

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 8.

In order to compare the signal coverage difference between BDS and GPS in more details, taking IM15 at the BIPM and TF06 at the NIM as instances, Figure 10 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, the similar statistics could be obtained from IM15 and TF06; for the IGSO satellite, TF06 has much better visibility including elevation and azimuth. For GPS, there are only MEO satellites for the civil service and thus, in Figure 10, 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 10.

However, from Figure 11, it can be seen that the number of BDS satellites in view at the BIPM position are in general, two or three, which is not fully adapted to the construction of good DOP (Dilution Of Precision) and continuous positioning. At TF06, there are considerably more satellites when counting the number of GEO

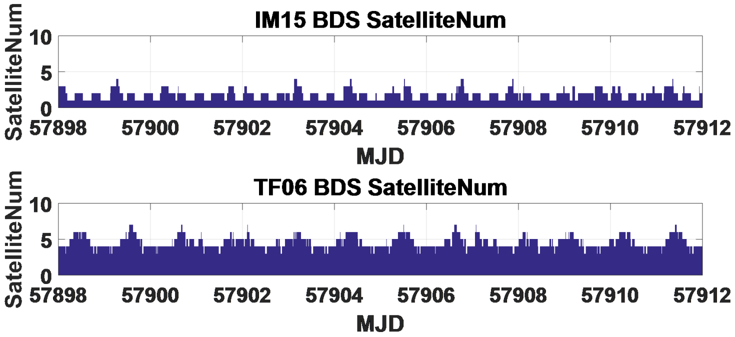

Figure 11. BDS satellite number statistics of IM15 (at the BIPM) and TF06 (at the NIM)

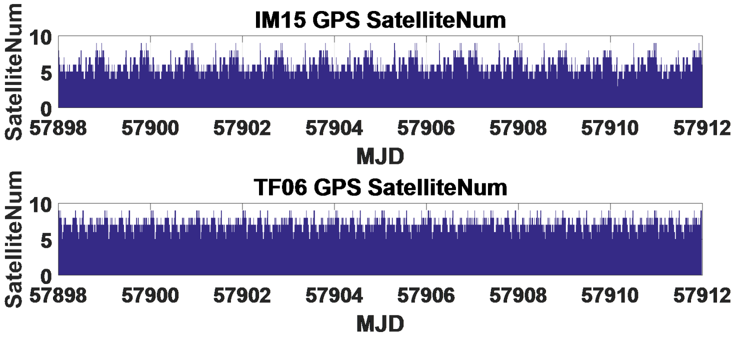

Figure 12. GPS satellite number statistics of IM15 (at the BIPM) and TF06 (at the NIM)

satellites, which generates the better signal coverage and also the BDS measurement in the Asia-Pacific region. In comparison, Figure 12 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 the 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 20000 kilometres. Stability (also including the measurement noise level) is evaluated using the CCD experiments at the different locations including Beijing and Paris and the experiments on the long baselines. Accuracy is mainly judged from the time transfer results on the long baselines after time link calibration.

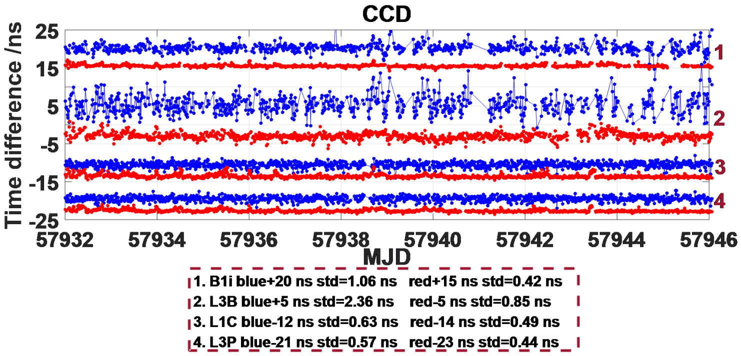

Figure 13. Time differences of BDS and GPS CCD experiments between IM15 and IM16 at the BIPM (blue), TF06 and TF07 at the NIM (red)

4.1. CCD Experiments at Different Sites

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

From Figure 13, 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 by BDS L3B code, which should be consistent with what is expected in terms of the law of propagation of the uncertainty [13]. To decrease the influence of the poor satellite coverage on the evaluation of the receiver performance, the 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 13 and TDEV in Figure 14, 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 at the averaging time of several thousand seconds. The B1i code of BDS has a bit better noise level than the L1C code of GPS at the NIM maybe due to its double bandwidth of the GPS C1/A signal.

4.2. Comparison among the Different Links on Long Baselines

The experiments on the long baselines, especially the inter-continental baselines, are designed to be implemented for the validation of the long-term stability and the accuracy in BDS time transfer. With the example of the common view of TF06 and IM15, on the Asia-Europe baseline, Figure 15 shows that only a few (less than four) satellites in each

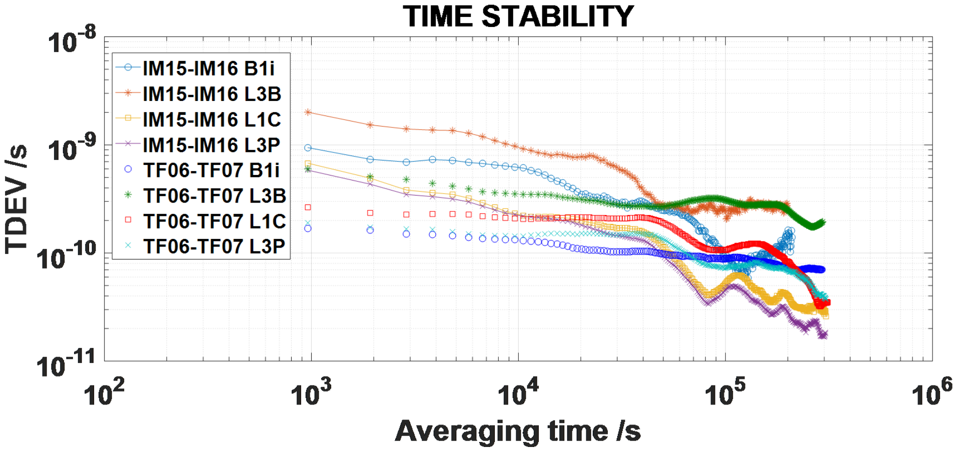

Figure 14. TDEV for the time differences of BDS and GPS CCD experiments between IM15 and IM16 at the BIPM, TF06 and TF07 at the NIM

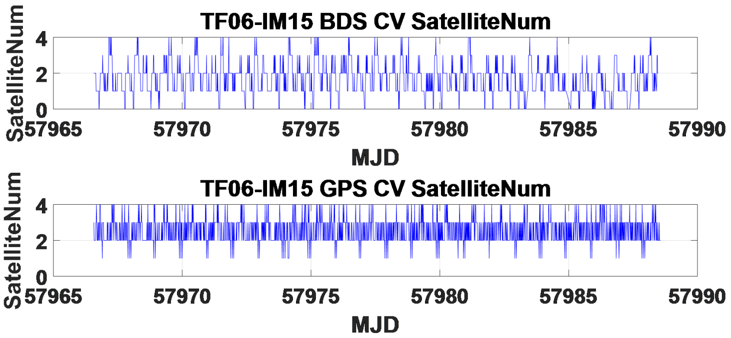

Figure 15. Satellite numbers in CV between IM15 (at the BIPM) and TF06 (at the NIM) for BDS and GPS

of the 16-minute measurement interval can be used in either GPS or BDS measurements because of the very long baseline length. For BDS, the number of satellites in common view is two for most of the time compared to three for GPS. Much fewer BDS satellites are visible for IM15 than those for TF06, although the baseline is long, all in-view (AV) mode may not embody full advantages, especially with the broadcast ephemeris. In the case of GPS, with the greater number of satellites at both locations in balance, generally more than seven satellites in this case, the AV mode should be more advantageous [14]. However, all the comparison results on the long baselines have been obtained through differentiating two receivers after averaging the measurements of all the satellites at the same epoch for each receiver in AV mode.

The receivers with the references of the Caesium clocks were selected so that the consistency between GPS time transfer and BDS time transfer is more easily and clearly observed for B1i and L3B codes measurements. The results of the receivers with the references of the Hydrogen maser 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

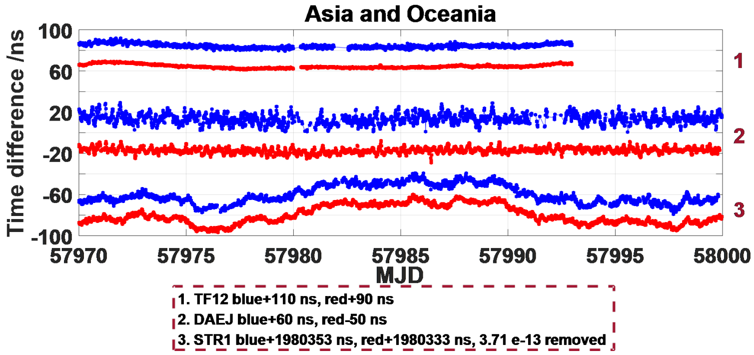

Figure 16. Time differences by BDS (blue) and GPS (red) between TF06 and the receivers in Asia and Oceania

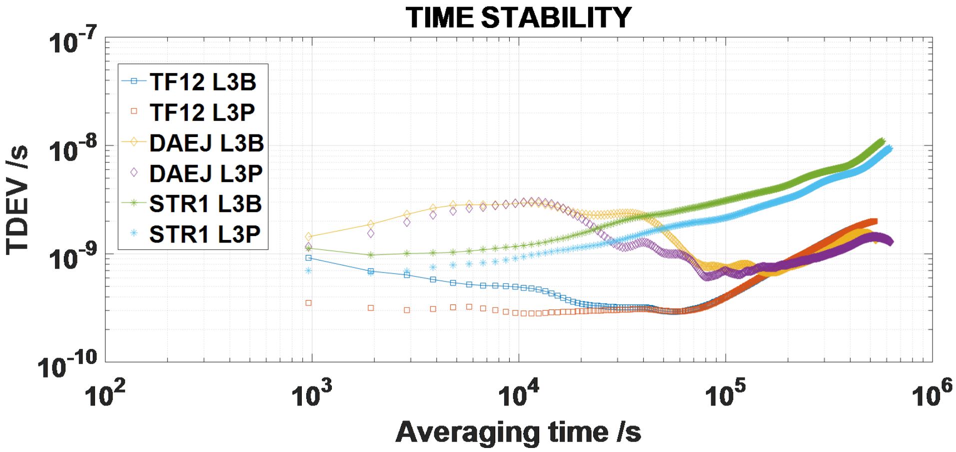

Figure 17. TDEV for the time differences by BDS and GPS between TF06 (at the NIM) and the receivers in Asia and Oceania

pivot receiver at the NIM. Since the sites are distributed in various regions, giving rise to different time transfer performances according to the satellite coverage statistics, the sites involved in the experiment have been divided in to the three groups: 1. Asia and Oceania, 2. Africa and Americas, and 3. Europe. However, DAEJ and HARB are using TRIMBLE NETR9 receivers that are not especially designed for time transfer and one site YEL2 is inside the Arctic.

From the time difference results in Figures 16 and 18, 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 Figure 17 and 19. Specially, some turbulence at DAEJ is observed for an unknown reason. The TDEV results from the links with the different IGS sites are not so close at short-term maybe due to the receiver not especially designed for time transfer, which may bring more uncertainty for the analysis, and different operation conditions, as described in last paragraph. However, there is a good agreement on the comparison at long-term between the BDS and GPS results between TF06 and the sites in Asia, Oceania, Americas and Africa.

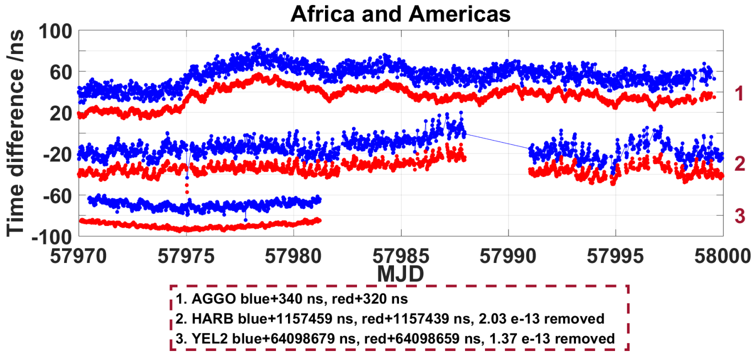

Figure 18. Time differences by BDS (blue) and GPS (red) between TF06 (at the NIM) and the receivers in Africa and Americas

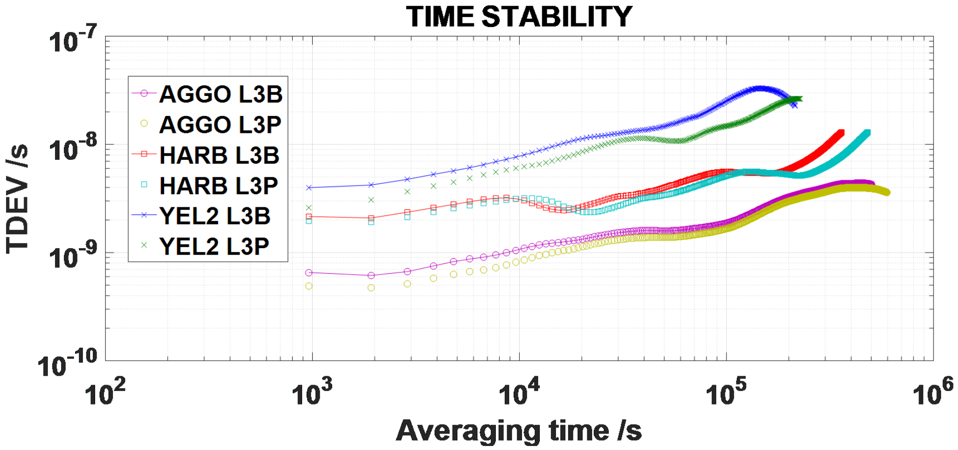

Figure 19. TDEV for the time differences by BDS and GPS between TF06 (at the NIM) and the receivers in Africa and Americas

More than 270 days data between MJD 57780 and MJD 58058 have been used in the comparison over the BIPM-NIM baseline presented in Figure 20. Results obtained with BDS and GPS with the pair of NIM-TF-GNSS-3 receivers, are in good agreement. The capacity and reliability for long time operation on this baseline could be seen. There are measurements for around 90% of the time. However, the small degradation in TDEV in Figure 21 between the results of BDS and GPS could derive from the missing data due to the poor satellite coverage.

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 Figure 28 and 29.

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

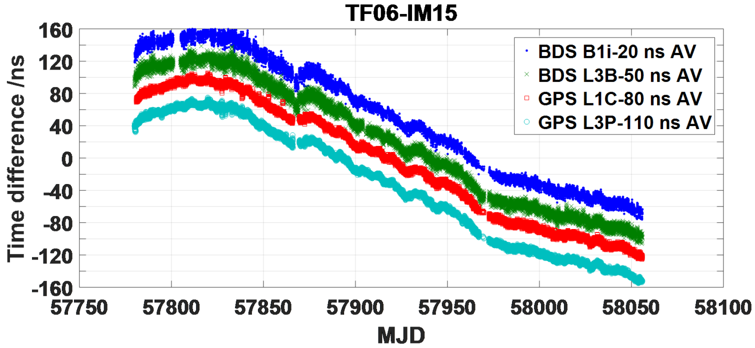

Figure 20. Time differences by BDS and GPS between TF06 (at the NIM) and IM15 (at the BIPM)

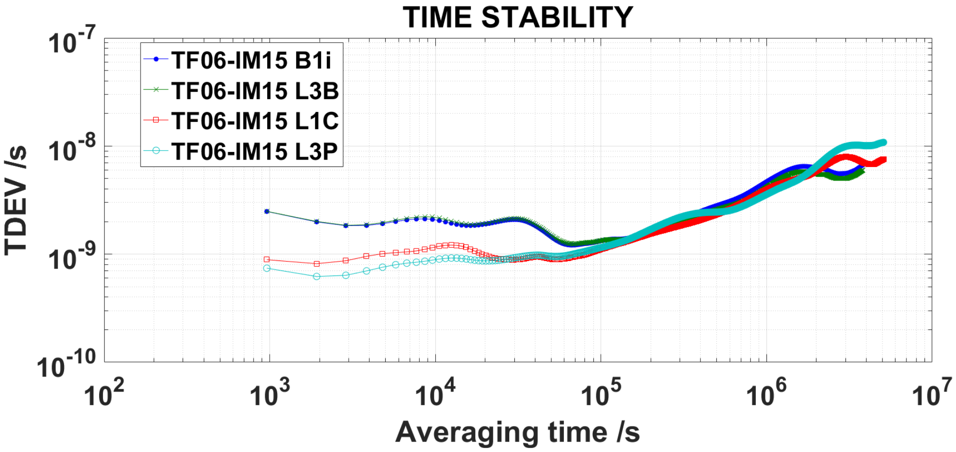

Figure 21. TDEV of the time differences by BDS and GPS between TF06 (at the NIM) and IM15 (at the BIPM)

Through IM15 and TP receivers, the approximate consistency could be observed between the results of BDS and GPS time and frequency transfer on IM15-TP baselines. TDEV shows agreement at long-term in Figure 23. On IM15-TP baselines, there are some obvious BDS observation gaps due to less time for observable satellite in this satellite coverage, and this coverage makes the time difference by BDS on IM15-TP baselines looks noisier that leads to the deviation of TDEV at short-term and also a bit deviation of TDEV at the long averaging time between BDS and GPS.

Time link calibration should be implemented for the accuracy evaluation of time transfer. Because none of the receivers are calibrated absolutely on BDS signals, for this target, the BDS calibration could be implemented by calibrating the whole BDS time link with two receivers by CCD experiments or by aligning the BDS links with other calibrated links, such as GPS time transfer links. All the involved BDS links between the pivot receiver TF06 and the other receivers were calibrated by the CCD experiments. For the GPS calibration, one calibration value for each receiver 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.

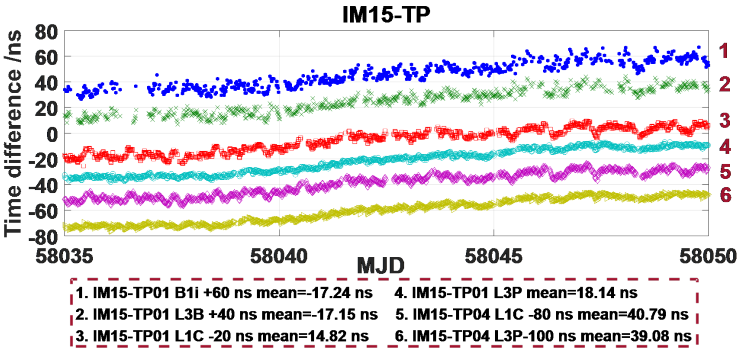

Figure 22. Time differences between IM15 (at the BIPM) and TP receivers

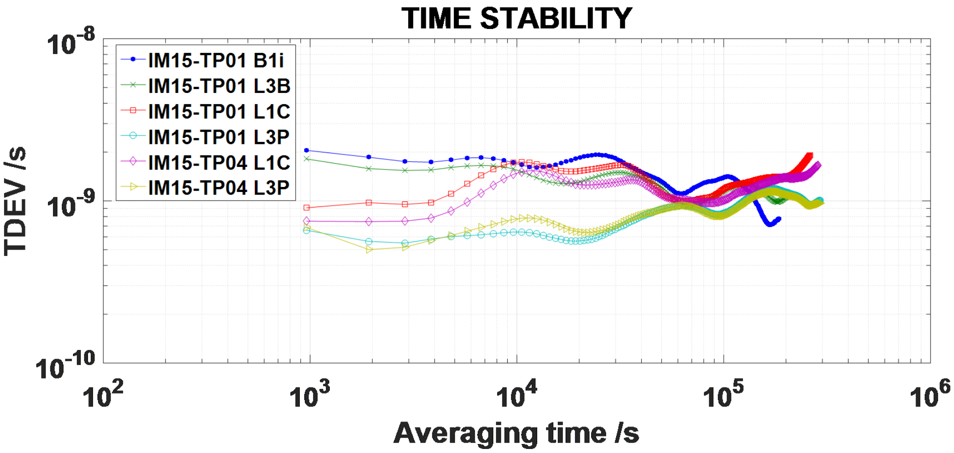

Figure 23. TDEV of the time differences between IM15 (at the BIPM) and TP receivers

Using the CCD methods for BDS link calibration, similar to differential calibration of 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 receiver 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 average of the time transfer results at all the epochs are computed 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 cesium 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 the better consistency.

Table 1. Calibration values for BDS links 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

5. SUMMARY AND EXPECTATION

A new time and frequency transfer system (NIM-TF-GNSS-3) capable of using the signals from BDS system and other GNSS constellations, and a new software (RinCGG) converting to CGGTTS (V2E) file from Rinex file, have been developed at the NIM. The type of receivers have been selected for the first time transfer by BDS over the Asia-Europe baselines, and significant laboratories in UTC network and other institutes in China are or will be equipped with the receivers for the full evaluation of BDS time transfer towards UTC contribution, and also one Czech site and some IGS tracking sites with RinCGG generating CGGTTS data have also been involved for the first evaluation. The different satellite signal coverage statistics for six continents (Asia, Oceania, Africa, South and North Americas, and Europe) have been studied, considering the satellite number, elevation and azimuth and SNR, which are adequate for time transfer across the 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 the experiments on the long baselines, especially the inter-continental baselines, for the estimation of the stability at long-term and the accuracy, the results show the agreement between BDS and GPS time transfer results in consideration of 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 the inter-continental baselines and this could be considered as a qualified method for time transfer towards UTC contribution.

The next steps will include all the data from the UTC laboratories in the 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), as well as some discussion about the involvement of the precise ephemeris, which is closer to the implementation in UTC computation.

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