Performance Evaluation of Near Real-time GNSS PPP Time Transfer with IGS Products

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Abstract: **The GNSS time transfer technology is the high precision time transfer method based on the navigation satellite system and has been widely applied in time and frequency. Benefiting from the development of GNSS time transfer technology and the expansion of user needs for real-time time service applications, real-time time transfer technology has become an important research direction. GNSS Precise Point Positioning (PPP) is one of the most commonly used methods of GNSS time transfer technology. With the development of the many facilities, the application of the real-time GNSS PPP has become wider and wider. In this paper, we demonstrate and evaluate the performance of the international GNSS service (IGS) products in the near real-time PPP time transfer technology. A set of the PPP solutions were computed from the observed data from the timekeeping laboratories, and three types of products provided by IGS, including Ultra-Rapid (IGU), Rapid (IGR), and Final (IGS final) orbit and clock offset products. IGS final and IGR products have extremely high accuracy and stability and are used as a reference for the time transfer with IGU product. The near real time clock offset and the comparison link performed with the IGU product can provide a time comparison service with an accuracy of 0. 5ns for near real time applications.**

Keywords: **Timing, Near real-time GNSS PPP, IGS products.**

I. INTRODUCTION

GNSS refers to GPS of the United States, GLONASS of Russia, GALILEO of Europe and BeiDou system of China (BDS). The GNSS time transfer technology is high precision time transfer method based on the satellite navigation system. The common-view method was the first satellite-based time transfer method [1] used by the BIPM, which now uses the all-in-view method [2]. In addition, the GNSS PPP time transfer method and two-way satellite time and frequency transfer (TWSTFT) have been developed [3,4]. PPP time transfer uses both code and the carrier phase. It requires careful consideration of various errors and accurate corrections to achieve global high precision time transfer [5]. The optical fiber time comparison link also has considerable high precision, but it also has high maintenance cost compared with the PPP method, and the construction is subject to various restrictions [6]. The PPP time transfer method has been widely used in international time transfer to provide high precision at low economic cost [7,8]. With the increasing real-time requirements of GNSS users for time services, real-time PPP has become an important development direction in recent years [9]. Although IGS products have high accuracy, only the prediction part of IGU products can be used for real-time calculations. The accuracy of this part of the data is lower than post processed products. The accuracy of the orbit and clock products greatly influences the accuracy of the PPP results. In order to meet the needs of real-time application users, IGS has formally provided real-time service (RTS) since 2013. The RTS products are real-time data stream containing corrections to the broadcast ephemeris. The RTS products have higher precision than IGU products [10,11]. But in a poor network environment, network transmission packet loss and data interruption have a great impact on the availability of real-time data streaming products [12,13]. In this case, the IGU products have better availability [14]. This article mainly investigates the performance of IGU products in near real-time applications.

IGS was established in 1992 by the International Association for Geodesy and it officially formally operations in 1994. IGS mainly provided GPS data in the early days of its establishment and it is now beginning to provide orbit and clock data of other GNSS. IGS is composed of more than 300 tracking stations, data analysis and processing centers, and data publishing centers worldwide. The properties of GPS orbit and clock products are listed in Table 1.

TABLE I. IGS PRODUCT INFORMATION (WWW.IGS.ORG/PRODUCT)

Product	Data type	Accuracy	Latency	Interval
Broadcast ephemerides	Orbits Satellite clocks	100 cm 5 ns RMS 2.5 ns STD	Real time	Daily
Ultra-rapid (predicted part)	Orbits Satellite clocks	5 cm 3 ns RMS 1.5 ns STD	Real time	15 min
Ultra-rapid (observed part)	Orbits Satellite clocks	3 cm 150 ps RMS 50 ps STD	3-9h	15 min
Rapid	Orbits Satellite clocks	2.5 cm 75 ps RMS 25 ps STD	17-41h	15 min 5min
Final	Orbits Satellite clocks	2.5 cm 75 ps RMS	12-18days	15 min 30s

II. PPP TIME TRANSFER

PPP requires precise satellite orbit and clock data along with a more accurate error correction model. The GPS observation codes include two kinds of code: C/A code and P-code. The code length and the symbol width of C/A code and P-code, respectively are 1023 bit and 0.97752 µs, 2.35E14bit and 0.097752 µs, so P-code has a lower ranging error of 0.29 m than C/A code's 2.9 m error. PPP uses the carrier wave with a considerably shorter wavelength and a ranging error reaching 0.0029 mm, two orders of magnitude lower than the P-code [15]. The improvement of ranging accuracy also increases timing accuracy.

When used for time transfer, PPP is a natural extension of the GNSS all-in-view method. PPP calculates the clock offset based on the dual-frequency carrier phase observation data and pseudorange observation data [16]. The local time independently maintained by a timekeeping laboratory is UTC(k), where k is the abbreviation of the timekeeping laboratory. Any time laboratory can assess UTC(k)-IGS by a GNSS timing receiver through PPP. On this basis, two different time laboratories can conveniently measure the offset between their local reference time. This comparison process requires support from corresponding high-precision ephemeris, and the stability of the reference time IGST needs to be equal to or better than the GNSS system time.

Near real-time PPP time transfer process use continuous updating precise orbit and clock products. This article mainly introduces the process with IGU products. The basic PPP process are introduced in the following part.

Figure 1 depicts the principle of PPP GNSS receivers equipped by each observation station to receive the messages and output Rinex format files, including station information, observed data, and broadcast ephemeris. High precision IGS orbit and clock products could be downloaded from IGS website. These observation data are the key parameter for the basic equation of PPP. The preliminary processing consists of several steps, including model modification, error detection, data interpolation, cycle slip detection and repair. Then the basic equations are estimated by Kalman filter. The estimated parameters would be deleted if they fail the in residual test, the retained parameters would be saved as position coordinate x, y, z and clock offset UTC(k)-IGST.

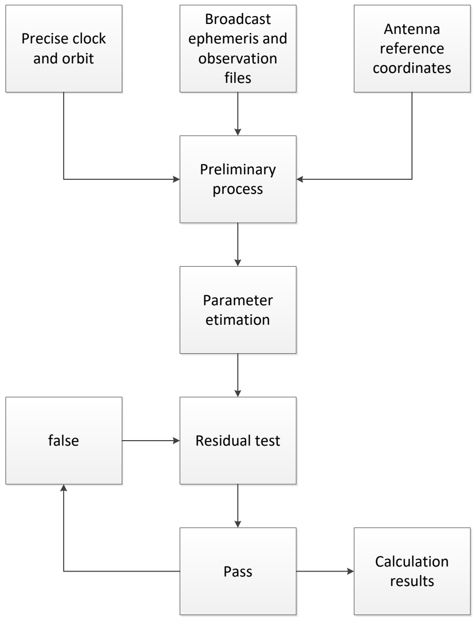

Fig. 1. Main process of precision point positioning method

In this article, the basic equations of PPP can be written as follows:

$$P^S_{(r,j)} = \rho^S_r + c\cdot dt_r - c\cdot dt_s + MF_w(e)\cdot Z_w + \gamma^S_j \cdot I^S_{r,1} + (d_{r,j} - d^S_j) + \varepsilon^S_{r,j}(P^S_{r,j}) \quad (1)$$

$$L^S_{r,j} = \lambda^S_j \cdot \phi^S_{r,j} = \rho^S_r + c\cdot dt_r - c\cdot dt_s + MF_w(e)\cdot Z_w - \gamma^S_j \cdot I^S_{r,j} + \lambda^S_j \cdot (N^S_{r,j} + b_{r,j} - b^S_j) + \xi^S_{r,j}(L^S_{r,j}) \quad (2)$$

where $P^S_{(r,j)}$ and $L^S_{r,j}$ are the code and carrier phase observations, ρ^S_r is geometric distance, dt_r and dt_s are time offset of receiver and satellite, $MF_w(e)\cdot Z_w$ is tropospheric wet delay, $\gamma^S_j \cdot I^S_{r,1}$ is ionospheric delay, $d_{r,j} - d^S_j$ and $b_{r,j} - b^S_j$ are hardware latency, $\varepsilon^S_{r,j}(P^S_{r,j})$ and $\xi^S_{r,j}(L^S_{r,j})$ are observation noise.

TABLE II. PROCESSING METHOD OF GNSS PPP

Parameters	Processing method
Observation	Dual-frequency undifferenced and uncombined PPP
Ionospheric delay	Dual frequency model
Tropospheric delay	Saastamoinen Model
Ambiguity estimation	Kalman filter

Important models are listed in Table II. The IGS final and IGR products are post processed products with considerable accuracy. The result with these products can be used as a reference. The result of forward and backward Kalman filter are combined by a fixed-interval smoother to obtain higher accuracy in the calculation process. IGU product are used for near real-time estimation. The Kalman filter state update as follows:

$$\begin{aligned} K &= P*H*(H'*P*H+R)^{-1} \\ Xp &= X + K*v \\ Pp &= (I - K*H')*P \end{aligned} \quad (3)$$

where X is the state vector, which includes the three-dimensional coordinates and clock offsets of the station, P is the covariance matrix of states, H is the transpose of the design matrix, v is the innovation (measurement - model), R is the covariance matrix of measurement error, n and m are the number of states and measurements, and Xp and Pp are states vector and covariance matrix of states after update.

The fixed-interval smoother is given as follow:

$$xs = Qs * (Qf^{-1} * xf + Qb^{-1} * xb) \quad (4)$$
$$Qs = (Qf^{-1} + Qb^{-1})^{-1}$$
$$xs = \begin{pmatrix} x & y & z & t \end{pmatrix}$$
$$Q = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} & \sigma_{xt} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} & \sigma_{yt} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} & \sigma_{zt} \\ \sigma_{tx} & \sigma_{ty} & \sigma_{tz} & \sigma_{tt} \end{pmatrix} = P \quad (5)$$

where xs is the matrix which includes the coordinates and clock offset of the station after the smoothing process. Qs, Qf and Qb are the corresponding matrix P in equation 3 for the smoother, forward filter and backward filter. The covariance of states σ can evaluate the error of each unknown quantity and directly determines the weights of forward and backward result in combined result. The combined mode is used to smooth and filter the calculation results, and mainly to reduce the impact of the one-way filter convergence process.

The accuracy of IGU products is lower than that of post processed products. And a single IGU product has only 2 days data. If only use forward filtering, the calculation results will have poor accuracy and precision, especially in the previous period of the data. And considering the latency of IGU products is 3 to 9 hours, the 3 to 9 hours of predict observation data of each IGU product is mainly used for near real-time application. Therefore, each calculation uses the data of this time period of the new file.

The near real-time clock offset between the two stations j and k can be solved with near real-time orbit and clock products by PPP. The specific implementation process includes following steps. First, PPP is used to calculate the offset between the two stations and the system time as UTC(k)-IGST and UTC(j)-IGST.. In the next step, the difference will be made between UTC(k)-IGST and UTC(j)-IGST. The high-precision results obtained by post processed the ephemeris and the values published by the BIPM can be used as references for near real-time time transfer.

III. DATA AND CALCULATION

The time offset between ORB, PTB and NTSC laboratory during the period from June 2, 2021 to June 22,2021 calculated by PPP are shown in following parts. We estimated the availability and quality of IGU orbit and clock offset product for near real time PPP application by comparing the IGU products, IGS final products, and IGR products along with data provided by BIPM.

The results of time link between time keeping laboratories published by BIPM are calculated with IGR products, and has a time interval of 5 minutes. Results with different time intervals may be required by near real-time time transfer users. The accuracy of the PPP calculation results is directly affected by the accuracy of the orbit and clock products used [17,18]. In order to facilitate the comparison with the reference value, the result calculated using the IGU products will also has a time interval for 5 minutes. IGU products provide time and orbit data with 15-minute sampling intervals. Compared with orbit data, the rate of change of clock data is fast. Therefore, we make interpolation process to the clock data. Researches show that linear interpolation is more suitable for interpolation of precise time data than polynomial interpolation [19]. Linear interpolation is used to interpolate the clock data of IGU products.

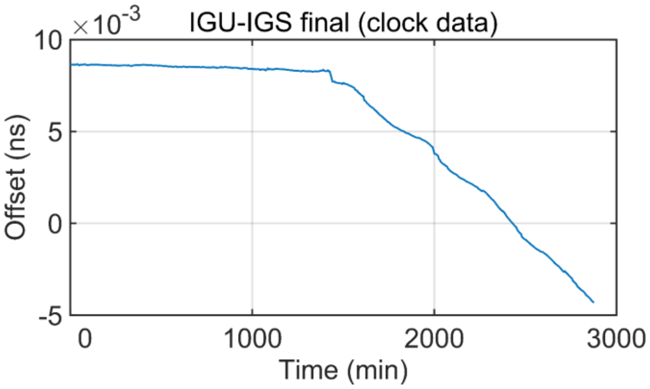

Fig. 2. The difference between IGU clock product and IGS clock product on satellite G01 from June 2, 2021 to June 4, 2021agnetization as a function of applied field.

Figure 2 shows the difference between interpolated IGU clock product and IGS clock product on satellite G01. Comparing with the difference of the IGU product relative to the IGS final product, the difference introduced by linear interpolation of the IGU product is several orders of magnitude smaller. The first 1440 minutes is the measured part of IGU product. This part of the data maintains a stable deviation with the reference value. The remaining part is the predicted part of IGU product. The deviation of this part of the data from the reference value obviously changes over time. The other 31 GPS satellites also showed the same conclusion. The standard deviation (STD) and maximum deviations of the IGU product and the reference value of each satellite in these two days are listed in Table III.

TABLE III. STD AND MAX OFFSETS (PS)

PRN	STD	Max	PRN	STD	Max	PRN	STD	Max
1	4.014	8.660	12	0.195	9.125	23	0.2308	8.7535
2	0.524	9.037	13	0.421	10.673	24	2.9841	20.0353
3	0.652	10.791	14	0.602	9.003	25	0.7103	8.8869
4	0.133	8.814	15	0.204	9.159	26	0.3050	9.5826
5	0.413	9.943	16	0.194	9.131	27	0.5343	8.6542
6	0.913	8.816	17	1.938	9.141	28	1.5717	9.0418
7	0.920	9.050	18	0.946	12.004	29	0.5471	9.0660
8	3.416	18.942	19	0.613	9.011	30	0.8263	8.5651
9	0.483	8.803	20	0.508	9.116	31	0.9295	11.5047
10	0.548	8.914	21	0.553	10.310	32	0.5285	10.2116
11	0.229	9.223	22	1.256	8.956			

It can be seen from Table III that the STD of the interpolated clock product is within 5ps compared with the standard value, and the maximum deviation is maintained within 50ps. The accuracy of the time product has little difference on the performance of each satellite. The interpolated IGU products still maintain the accuracy officially announced by IGS and can be used.

This part will perform the analysis and evaluation of the availability of IGS products from multiple aspects through the time comparison result of the two stations.

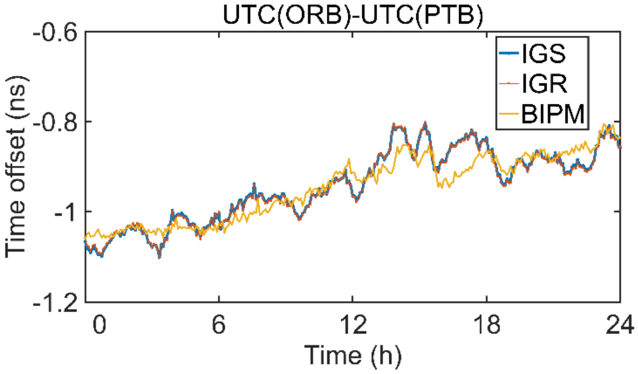

Fig. 3. Time comparison results of ORB and PTB sites with post processed products

Figure 3 shows the time offset between ORB and PTB calculated with IGS and IGR products along with time offset published by the BIPM on June 9, 2021. To obtain higher accuracy and stability, combined method is applied in the calculation process of post processed products. It can be seen that the results of the two products and the published value have a small deviation within 0.1ns caused by the method. The results of IGR products and IGS final products calculated by the combined method maintains a small deviation within 0.01ns. IGR products have considerably shorter latency than IGU products. For near real-time applications, the result with IGR products can be used as the reference value for the result with IGU products and the post processed calculation results are used to verify the quality of the near real-time results. In the following part, the data provided by the BIPM is uniformly used as the reference value of the near real-time PPP results with IGU products, and the STD index of the time comparison result is mainly investigated.

As mentioned above, an IGU file contains two days of data, the predicted part data from 24 hours to 48 hours is more important for near real-time calculations. The improved method is used to obtain higher precision results. The data calculated by forward filter are recorded as IGUF, and the data smoothed are recorded as IGU1.

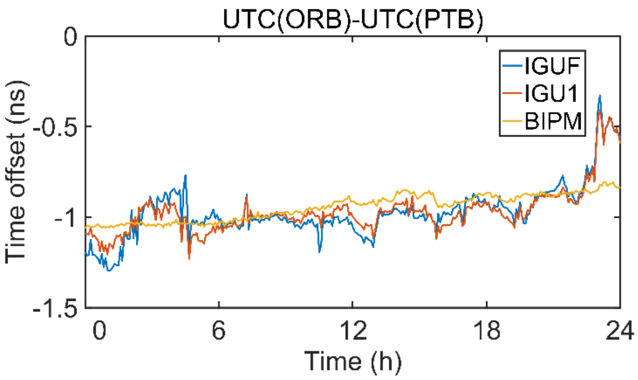

Fig. 4. Time comparison results of ORB and PTB sites with IGU products

Figure 4 shows the time transfer results of ORB and PTB laboratory, calculated by the above two methods along with the result published by BIPM on June 9, 2021. It can be seen that the results calculated using the two methods of the IGU product maintain a similar trend to the reference value within a certain range. In the last two hours, the calculation results using IGU products have a larger deviation from the reference value. The result of the improved method has less fluctuation relative to the reference value.

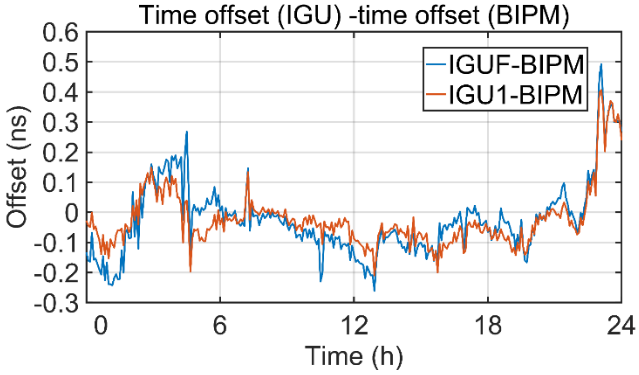

Fig. 5. The deviation of time comparison results of ORB and PTB sites with IGU products

Figure 5 shows the deviation between the results of the two methods and the reference value. It can be seen that the deviation of the two results in the first 22 hours is maintained within 0.3ns. The STD of the IGUF result is 0.1237ns and IGU1 result is 0.0997ns. This result indicates that the improved forward filter method can reduce the error caused by the slow convergence speed of the filter, and has a better performance overall. The STD of the calculation results of the two methods in the first 12 hours are 0.1077ns and 0.0620ns respectively. The method improves accuracy and precision more for data in this period, which is important for near real-time applications. In the following part, the calculations of IGU products adopt the improved method.

Near real-time PPP requires continuous, real-time updated precise orbit and clock data. One IGU product only provides precise orbit and clock data in two days, and predicted data for one day. New IGU products must be downloaded continuously to update precise orbit and clock data for near real-time process. Since IGU products have a latency of 3 to 9 hours, and the data of each file is 6 hours apart, the 3 to 9 hours of the predicted data of each IGU product is used in the calculation. The accuracy and precision of the measured part of the IGU product is much higher than the predicted part. To make full use of data with higher precision and accuracy, the new product and observation data are used for calculation and replace the old ones. The first file can be used to the 9th hour of the predicted part. Then each new file is used to calculate the data for the next 6 hours to achieve continuous near real-time process.

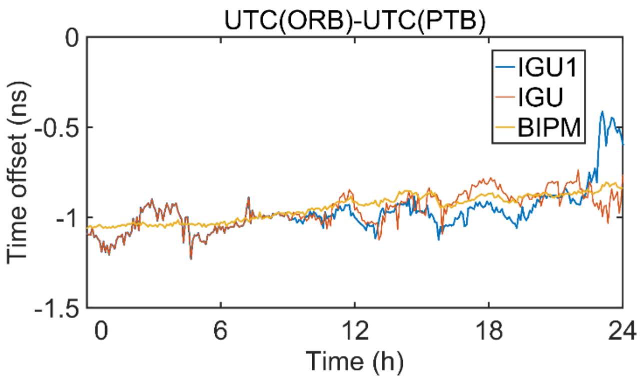

Fig. 6. Time comparison results of ORB and PTB sites with IGU product and updating IGU products

Figure 6 shows the time transfer results of ORB and PTB laboratory calculated with one IGU product and four IGU products, along with the result published by BIPM on June 9, 2021.The result of using one IGU product is recorded as IGU1. The result of using four continuous IGU products is recorded as IGU. The first 9 hours of the result are calculated using the first product, and the subsequent 9 to 24 hours are calculated using the updated products. The two results use the same data in the first 9 hours, so the curves are coincident. In the last 3 hours, the IGU1 result deviates greatly from the reference value, and the result calculated with continuous updated products maintains certain deviations around the reference value. The deviation value is shown in Fig.7.

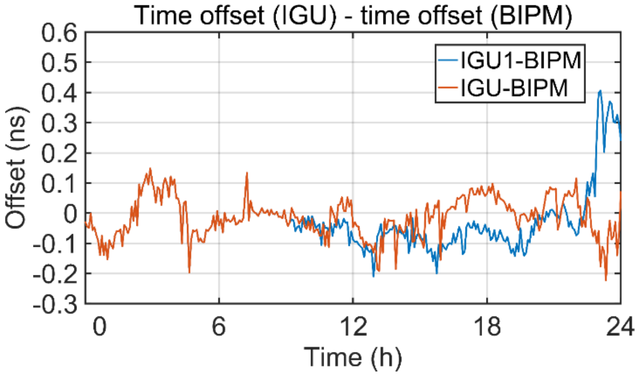

Fig. 7. The deviation of time comparison results of ORB and PTB sites with IGU products and updating IGU products

Figure 7 shows the deviation of the two calculation results from the reference value. The STD of the results of the two methods within 24 hours is 0.0997 and 0.0597, the result calculated using updating products achieves higher accuracy. The STD from 9 to15 hours is 0.0393ns and 0.0364ns respectively, from 15 to 21 hours is 0.0433ns and 0.0426ns respectively, and the STD from 21 to 24 hour is 0.1632ns and 0.0807ns respectively. In the three selected time periods, using updating products achieves higher accuracy, especially in the last three hours when the predicted time is long. It can be seen that apart from the last three hours, the results of a single IGU product and the continuous updating IGU products have approximate accuracy. If the product is postponed to update, the old product can be used for calculation in about 6 hours next.

We use observation data from ORB, PTB and NTSC laboratory, and IGU products from June 2 to June 22, 2021, a total of 20 days for simulation calculations, to evaluate the performance of long-term near real-time time transfer of IGU products. In the evaluation of long-term results, STD and frequency stability are used as the main evaluation indicators. The main indicator is the overlapped Allan deviation (ADEV). The ADEV is used to evaluate the frequency stability [20]. The ADEV of time links performs both the stability of UTC(k) maintained by the two stations and the stability of the time links. ADEV of time transfer result in the same period of the same stations can reflect the performance of the transmission link and evaluate the performance of the IGU products.

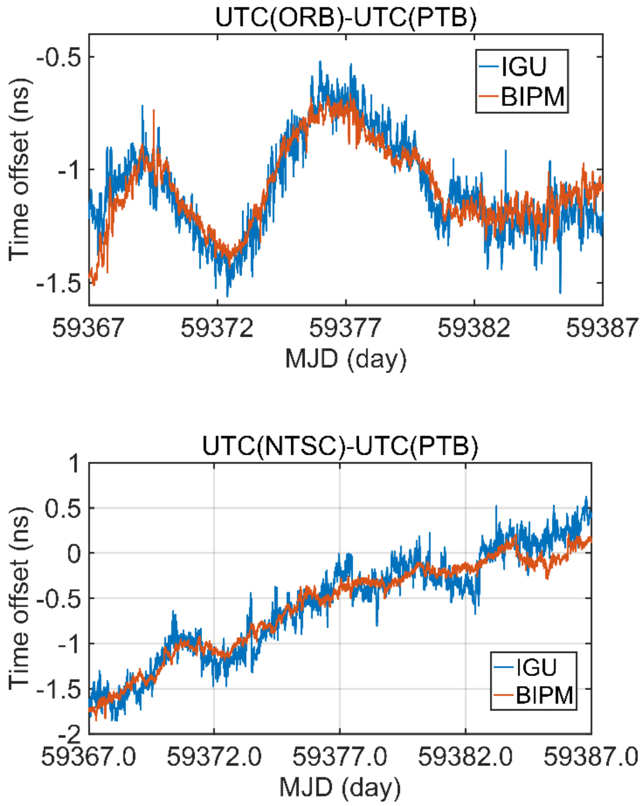

Fig. 8. Time comparison results of ORB and PTB sites with IGU product during 20 days

Figure 8 shows the time transfer results of ORB and PTB laboratory and the results of NTSC and PTB laboratory calculated with IGU products, and the corresponding result published by BIPM from June 2, 2021 to June 22, 2021. Although the sites used are different, both sets of results show the same characteristics. It can be seen from the pictures that the results calculated using IGU products keep the same trend with the reference value in the long-term of 20 days. The results calculated using IGU products have larger noise and lower accuracy, but it still stays within 1ns from the reference value. The corresponding deviations are shown in figure 9 and figure 10.

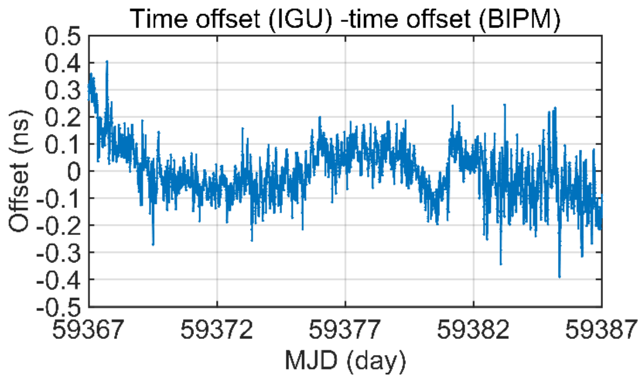

Fig. 9. The deviation of time comparison results of ORB and PTB sites with IGU products during 20 days

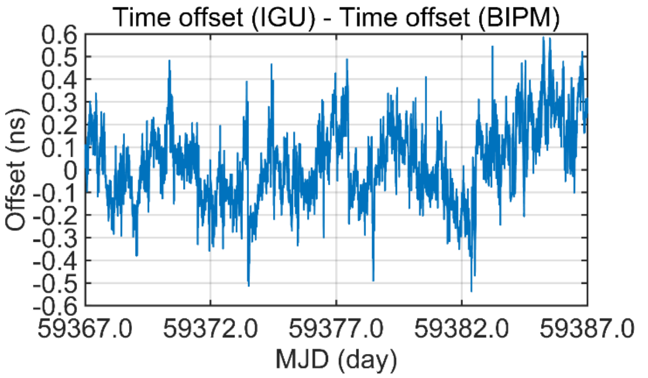

Fig. 10. The deviation of time comparison results of NTSC and PTB sites with IGU products during 20days

Figure 9 shows the deviation of the calculation results of ORB and PTB laboratory from the reference value. Figure 10 shows the deviation of the calculation results of NTSC and PTB laboratory from the reference value. Both of the deviation results maintain within 0.6 ns during 20 days. The deviation of the result calculated using IGU products is not stable in the short-term and may deviate from 0, but it fluctuates around 0 in most period. The deviation result of ORB and PTB laboratory maintains within 0.3ns in more than 99% of the total time, and the STD is 0.0945ns. The deviation result of NTSC and PTB laboratory maintains within 0.5ns in more than 99% of the total time, and the STD is 0.1632ns. The result of NTSC and PTB laboratory show larger STD, which may be caused by the long distance between the two stations and the receiver and clock performance. The results show that the improved calculation method using IGU products can achieve continuous and available near real-time time transfer within 0.5 ns of the two stations.

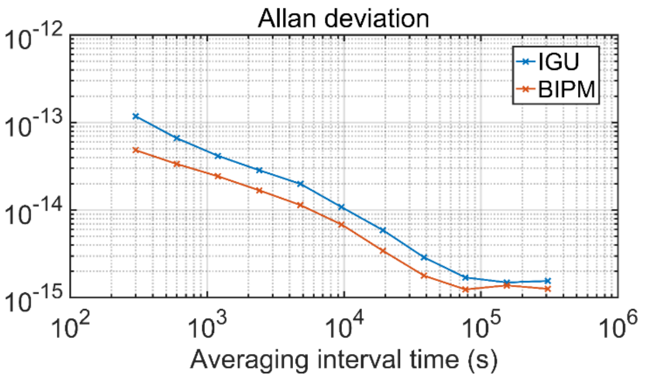

Fig.11. Allan variance of the time comparison result between ORB and PTB

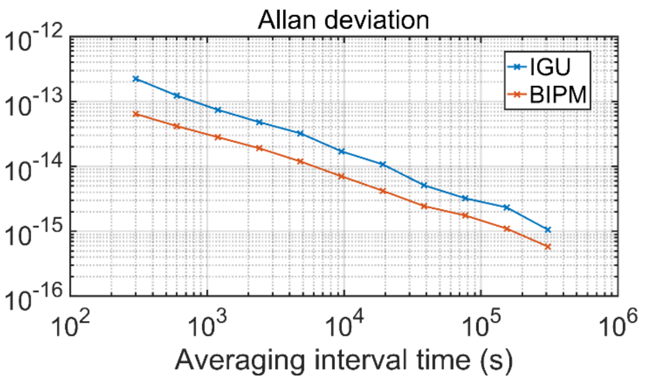

Fig.12. Allan variance of the time comparison result between NTSC and PTB

The frequency stability of UTC (ORB)-UTC (PTB) and UTC (NTSC)-UTC (PTB) in the 20 days are shown in figure 11 and figure 12. The results include two sets of data calculated using IGU products and the results published by BIPM. The frequency stability of UTC (ORB)-UTC (PTB) calculated using IGU products and the results published by BIPM in 300s are 1.18e-13 and 4.83e-14. The frequency stability of UTC (NTSC)-UTC (PTB) calculated using IGU products and the results published by BIPM in 300s are 2.24e-13 and 6.43e-14. These data indicate that the result calculated using IGU products has worse frequency stability in short term. The frequency stability of UTC (ORB)-UTC (PTB) calculated using IGU products and the results published by BIPM in 3840s are 2.88e-15 and 1.78e-15. The frequency stability of UTC (NTSC)-UTC (PTB) calculated using IGU products and the results published by BIPM in 3840s are 5.10e-15 and 1.75e-15. These data indicate that the result calculated using IGU products has considerable frequency stability in long term. Although the short-term stability of the calculation results of IGU products is poor, the difference from the results calculated by BIPM using IGR products is within an order of magnitude.

IV. CONCLUSIONS

In this article, we investigated a complete series of theories, and analysed the corresponding performance of near real-time time transfer by using IGU product. By comparing the offsets between the interpolated IGU product and IGS final product it can be found that the accuracy of the orbit and clock data of the IGU product is slightly worse than that of the high-precision post processed product, and the predicted value of the clock data does not fit the observation data well. The accuracy of the time offset calculated by the GNSS PPP method is directly affected by the accuracy of the clock and orbit products. Improved mathematical methods and real-time update of precision orbit and clock error data can effectively improve the accuracy and precision of near real-time time transfer results achieved by IGU products. If the file update is delayed, the last IGU products can still be used within a few hours to obtain high-precision calculation results and provide available near real-time services in poor network environment. The result of near real-time GNSS PPP time transfer using IGU product is extremely close to the high precision post processed results published by BIPM on the order of sub-nanosecond, and it also has considerable stability, which can be applied for the near real-time time transfer application with sub-nanosecond accuracy. To sum up, the results of this paper show that the near real-time GNSS PPP time transfer realized by IGU product can meet the sub-nanosecond application requirements, the accuracy of time transfer can be better than 0.5 ns, and the stability can reach 1E-14 with the averaging interval time of 3600 seconds.

V. ACKNOWLEDGMENT

This research is based on the products provided by the IGS, Calculations are based on the Rtklib software. The authors are grateful to reviewers for their helpful comments and suggestions!

GNSS data used are publicly available from data centers of the IGS (International GNSS Service)

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