Using IGS RTS Products for Real-Time Subnanosecond Level Time Transfer

Guojun Li, Yuting Lin, Fengfeng Shi, Jialin Liu, Yuting Yang and Junwen Shi

Abstract Time transfer by precise point positioning has the defect of long latency resulting from IGR products. GPS common-view can be updated once every 16 min, but with a precision of about 3–5 ns. A real-time precise point positioning time transfer algorithm using IGS RTS (Real-time Service) products was proposed. It was proved to be practical through the time transfer experiments among 4 time laboratories in Western Europe. The time transfer results show that the accuracy of the new algorithm can be reach to 0.30 ns for RMS and 0.25 ns for STD. Moreover, the stability of the time transfer results is up to 2E−15 at 1 day averaging.

Keywords IGS RTS · Time transfer · Real-time precise point positioning Subnanosecond

1 Introduction

Presently, the time transfer methods for time laboratories participating in TAI (International Atom Time) consist of GPS AV (GPS All-in-view) [1], GLONASS AV (GLONASS All-in-view) [2], GPS PPP (GPS Precise Point Positioning) [3], TWSTFT (Two-way Satellite Time and Frequency Transfer) and et al. As an important time transfer method, GPS PPP accounts for 48% time links with increasing proportion in recent years [4]. It's widely used in worldwide time laboratories.

GPS PPP has great advantages in high-precision time and frequency transfer over a long distance. It can provide a frequency stability of 1E−15 to 1E−16 over an averaging period of 1 day, moreover, as type B uncertainty is less than 0.3 ns [5, 6]. However, GPS PPP requires precise ephemeris products. The ephemeris

G. Li (✉) · Y. Lin · F. Shi · J. Liu ·
Y. Yang · J. Shi
Beijing Satellite Navigation Center, Beijing, China
e-mail: 1010551750@qq.com

J. Sun et al. (eds.), *China Satellite Navigation Conference (CSNC) 2018 Proceedings*, Lecture Notes in Electrical Engineering 497,
https://doi.org/10.1007/978-981-13-0005-9_40

products used in BIPM for GPS PPP time transfer is the IGR (IGS Rapid), whose latency is 17–41 h [7]. The IGU is a real-time precise ephemeris product for real-time cm-level positioning. The accuracy of satellite clocks is about 0.15 ns for the IGU observed half, and is 3 ns for the IGU predicted half. Thus, the IGU is unusable for real-time subnanosecond level time transfer.

There are many researches on GPS PPP, which mainly focus on post-processing time transfer [8, 9]. Many time laboratories can hardly monitor the real-time time and frequency signals. The methods for nanosecond and subnanosecond level time transfer are far from practical applications. In this paper, firstly, we briefly introduced the organization of IGS RTS and the usages of IGS RTS products. Secondly, the accuracy and availability of IGC01 were analyzed. Thirdly, the experiment, GPS PPP time transfer with IGC01 among four time laboratories in Western Europe, proved that it was feasible to realize subnanosecond level time transfer with IGS RTS products.

2 The IGS RTS Products

2.1 The Organization of the IGS RTS

Since its inception in 1994, IGS has produced high-quality GNSS data products from a cooperative global infrastructure. The IGS products enable access to the definitive global reference frame for scientific, educational, infrastructure, and people's livelihood. With the growing developments of GNSS application, IGS users have expressed a desire for real-time products. In 2001, the IGS Real-Time Working Group (RTWG) was established [10]. During the IGS 2002 Workshop, held under the theme "Towards Real-Time", a framework for development of a real-time service (RTS) was defined [11]. In 2007, the IGS Real-time Pilot Project started to be constructed, and the RTWG declared that the pilot project had reached the initial operating capability.

The IGS RTS is overseen by the RTWG. Parts of importation organizations are as follow [12]:

(1) Analysis centers, including BKG, CNES, DLR, GFZ, ESA/ESOC, GMV, Geo++, NRCan, TUW and WUHAN, has responsibility for the generation of precise ephemeris products with observations provided by global GNSS tracking networks. In addition, NRCan, ESA/ESOC, and BKG are in charge of supervision, coordination and operation.
(2) Combination centers, including ESA/ESOC, BKG and NRCan, produce the official combination products by realigning, detection and elimination of outliners and averaging.
(3) The products distribution centers, including two primary products distribution centers and a number of secondary centers, use Networked Transport of RTCM via Internet Protocol (NTRIP) for streaming GNSS and differential correction

Table 1 The information of IGS RTS products

RTS products	Ref point	RTCM messages
IGS01	APC	1059 (5), 1060 (5)
IGC01	CoM	1059 (5), 1060 (5)
IGS02	APC	1057 (60), 1058 (10), 1059 (10)
IGS03	APC	1057 (60), 1058 (10), 1059 (10) 1063 (60), 1064 (10), 1065 (10)

data over the Internet. Users must complete the online subscriber registration. After authentication, users will be in contact with login and be access to the RTS streams.

The official products currently include IGS01/IGC01, IGS02 and IGS03 [12] (Table 1). IGS01/IGC01 is a single-epoch GPS combination solution. The solution epochs in this product are completely independent of each other. IGS02 is a Kalman filter combination product with precise ephemeris products estimated by individual analysis centers. IGS03 is similar to IGS02, except that IGS03 contains the GPS and GLONASS corrections which are offered as an experimental product.

2.2 *Real-Time Satellite Precise Ephemeris and Clocks*

(1) Real-time precise satellite ephemeris

RTS products are the corrections refer to broadcast navigation data. The orbit corrections are defined in radial, along-track and cross-track in satellite body-fixed coordinate system. If the orbit correction vector is $\begin{bmatrix} \delta O_{\mathrm{r}} & \delta O_{\mathrm{a}} & \delta O_{\mathrm{c}} \end{bmatrix}^{\mathrm{T}}$ at epoch t_0, and the velocity vector is $\begin{bmatrix} \delta \dot{O}_{\mathrm{r}} & \delta \dot{O}_{\mathrm{a}} & \delta \dot{O}_{\mathrm{c}} \end{bmatrix}^{\mathrm{T}}$. Three steps are required to compute the real-time satellite position at current epoch. Firstly, compute the real-time correction in satellite body-fixed coordinate system at current epoch t [13].

$$\begin{bmatrix} \delta_{\mathrm{r}} \\ \delta_{\mathrm{a}} \\ \delta_{\mathrm{c}} \end{bmatrix} = \begin{bmatrix} \delta O_{\mathrm{r}} \\ \delta O_{\mathrm{a}} \\ \delta O_{\mathrm{c}} \end{bmatrix} + \begin{bmatrix} \delta \dot{O}_{\mathrm{r}} \\ \delta \dot{O}_{\mathrm{a}} \\ \delta \dot{O}_{\mathrm{c}} \end{bmatrix} (t - t_0) \tag{1}$$

where δ_{r}, δ_{a}, and δ_{c} are the radial, along-track and cross-track corrections. The orbit corrections must be transfer to geocentric corrections. Secondly, compute the transformation matrix:

$$\mathbf{R} = \begin{bmatrix} \frac{\dot{\mathbf{r}}}{|\dot{\mathbf{r}}|} \times \frac{\mathbf{r} \times \dot{\mathbf{r}}}{|\mathbf{r} \times \dot{\mathbf{r}}|} & \frac{\dot{\mathbf{r}}}{|\dot{\mathbf{r}}|} & \frac{\mathbf{r} \times \dot{\mathbf{r}}}{|\mathbf{r} \times \dot{\mathbf{r}}|} \end{bmatrix}^{\mathrm{T}} \tag{2}$$

where $\mathbf{r}$ is the satellite broadcast position vector and $\dot{\mathbf{r}}$ is the satellite broadcast velocity vector. Thirdly, apply the real-time corrections to the broadcast coordinates.

$$\begin{bmatrix} X_s \\ Y_s \\ Z_s \end{bmatrix} = \begin{bmatrix} X_{brdc} \\ Y_{brdc} \\ Z_{brdc} \end{bmatrix} - \mathbf{R} \begin{bmatrix} \delta_r \\ \delta_a \\ \delta_c \end{bmatrix} \tag{3}$$

where X_s, Y_s, Z_s are the satellite coordinate in the ECEF coordinate system. X_{brdc}, Y_{brdc}, Z_{brdc} are the satellite position computed from broadcast ephemerides.

The RTS products refer to the satellite CoM (Center of Mass) or APC (Antenna Phase Center). There is no need to apply APC correction if the products refer to the APC, such as IGS01, IGS02and IGS03. However, the APC correction must be applied if the products refer to the CoM.

(2) Real-time precise satellite clocks

If the polynomial coefficients in RTS products are C_0, C_1 and C_2 at epoch t_0. The precise satellite clock correction at current epoch t can be calculated as follows:

$$\delta C = C_0 + C_1(t - t_0) + C_2(t - t_2)^2 \tag{4}$$

Apply the corrections to the broadcast clock:

$$dt^{sat} = dt^{sat}_{brdc} + \frac{\delta C}{c_{light}} \tag{5}$$

where dt^{sat}_{brdc} is the broadcast clock corrected with relativistic effect at current epoch t. c_{light} is the speed of light in vacuum.

2.3 The Accuracy and Availability of the IGS RTS Products

To monitor the accuracy of the RTS products, the daily comparison reports between the real-time products of each analysis center and the IGR are provided by EAS/ESOC. The precision of precise point positioning with the RTS products is monitored. Appending on the statistical results in recent years [14], the satellite orbit accuracy is about 5 cm, as same as IGU. While the satellite clock accuracy is about 0.3 ns, which is much better than the accuracy of the IGU predicted half.

For the convenient to analysis, we take IGC01 as an example to analyze its accuracy and availability owing that its reference is same with the IGR's. The software BNC [15] recommended by the official was used to store the IGC01 streams from WUHAN (http://gnsslab.ntrip.cn) in RINEX at intervals of 30 s. The totaled data span is 16 day, from 2017-09-10 to 2017-09-25.

It's remarkable that the real-time satellite clocks of individual analysis center are possible in different time scale. The difference of the time references must be taken into consideration when analyze the accuracy of the satellite clocks. In this paper we take the average value of all the satellite clocks in each epoch as the time

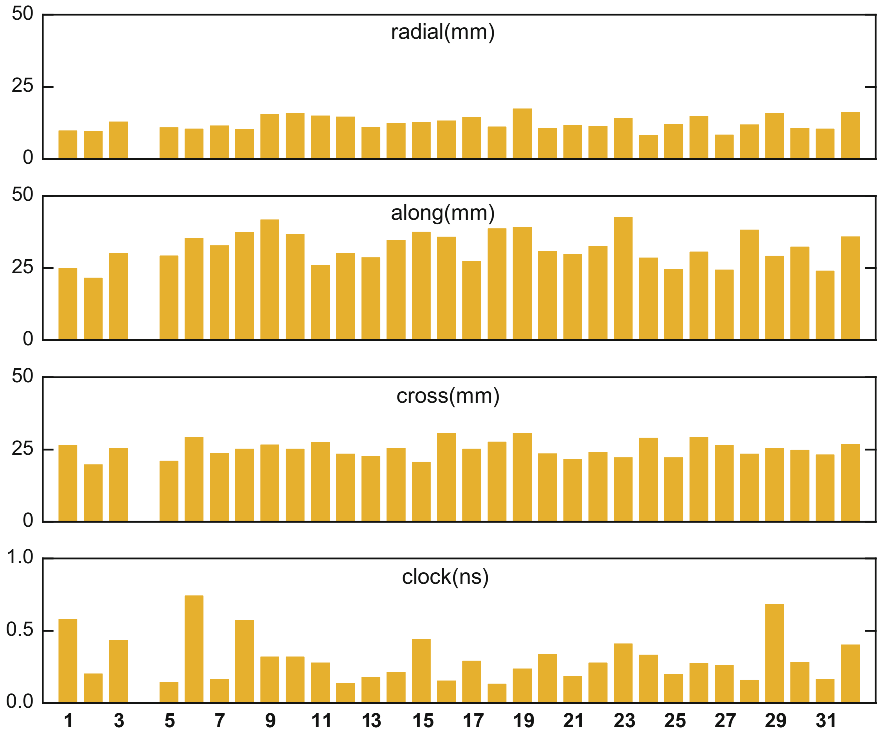

Fig. 1 The RMS of IGC01 ephemeris and clock

reference. In addition, the clock correction resulting from the orbit radial correction is applied. Figure 1 shows the RMS of the satellite orbit and clock difference of the IGC01 against the IGR. Table 2 presents the statistic of the IGC01 products.

As shown in Fig. 1 and Table 2, The RMS of the satellite orbits in IGC01 is 33 mm for the radial component, which is 1–2 times better than 32 mm for the along-track component and 26 mm for the cross-track component. The STD and the RMS of the satellite 3D-orbit is 20 and 44 mm. The STD and the RMS of the satellite 3D-orbit are respectively 20 and 44 mm. The STD and the RMS of the satellite clocks are respectively 0.12 and 0.30 ns. However, the accuracy of a small number of the satellite clocks is slightly low, such as G06 and G29, the RMS is up to 0.75 ns. This may be related to the data span or the performance of the satellite clocks.

The availability of the real-time products directly determines the reliability of the time transfer method. The availability is 99.99% for the broadcast ephemeris, 99% for the IGS final, 95% for the IGU and the IGR. Figure 2 shows the distribution of data interruptions in IGC01. Figure 3 shows the average availability of each satellites.

Table 2 The statistic of IGC01 ephemeris and clock

IGC01	Statistic type	Max/PRN	Min/PRN	Avg.
Orbit (mm)	STD	27.6/G19	13.6/G02	19.9
	RMS	53.1/G19	31.3/G02	43.5
Clock (ns)	STD	0.31/G06	0.08/G27	0.12
	RMS	0.75/G06	0.14/G18	0.31

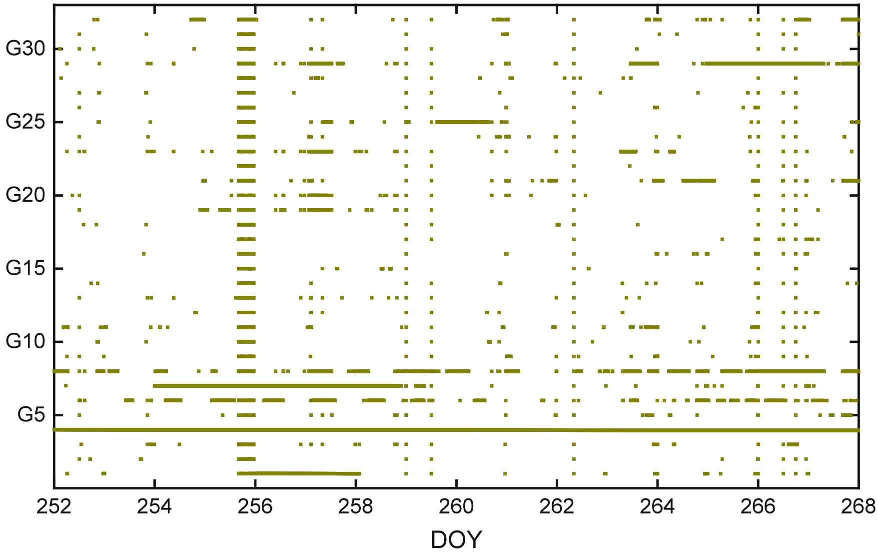

Fig. 2 The distribution of data interruptions in IGC01

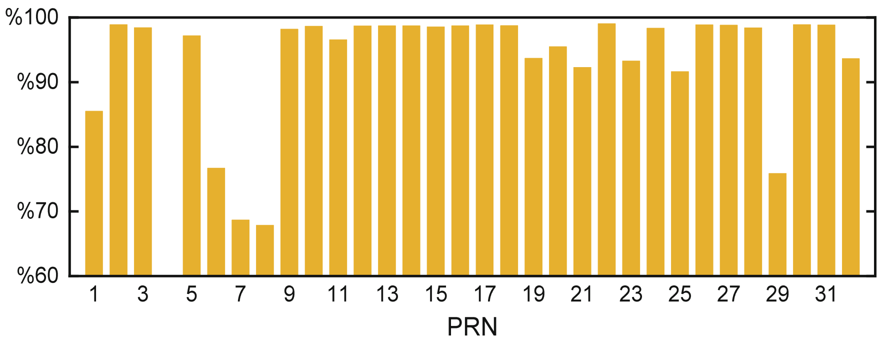

Fig. 3 The availability of IGC01

As shown in Figs. 2 and 3, the availability of the IGC01 for most of the satellites is up to 98%. Except for G04, the average availability of the other satellites is about 93.8%, which is slightly lower than the availability of about 95% obtained from the long term statistics.

3 GPS PPP Time Transfer Based on the RTS Products

3.1 GPS PPP Time Transfer

The traditional ionosphere-free model of GPS PPP time transfer is as follows [14]:

$$P_3 = \rho + cdt^r - cdt^s + T + b^r_{P3} - b^s_{P3} + \varepsilon_{P3} \tag{6}$$

$$\Phi_3 = \rho + cdt^r - c\mathrm{d}t^s + T + b^r_{\Phi_3} - b^s_{\Phi_3} + \lambda_3 N_3 + \varepsilon_{\Phi_3} \tag{7}$$

where P_3 and Φ_3 are respectively the ionosphere-free combinations of the pseudorange measurements and the carrier phase measurements. ρ is the topocentric distance between satellite and receiver. c is the speed of light in vacuum. dt^r and dt^s are the satellite and receiver clock errors. T is the slant tropospheric delay. b^r_{P3} and b^s_{P3} are the satellite and receiver code hardware delays. $b^r_{\Phi_3}$ and $b^r_{\Phi_3}$ are the frequency-dependent carrier phase hardware delays for satellite and receiver. λ_3 is the narrow-lane wavelength. N_3 is the narrow-lane ambiguity. ε_{P3} and ε_{Φ_3} are unmodeled errors.

A reparameterized version of Eqs. (6) and (7) which eliminates liner dependencies can be written as:

$$P_3 = \rho + cdt^r_{P_3} - cdt^s_{P_3} + \varepsilon_{P_3} \tag{8}$$

$$\Phi_3 = \rho + cdt^r_{P_3} - c\mathrm{d}t^s_{P_3} + T + \lambda_3 N'_3 + \varepsilon_{\Phi_3} \tag{9}$$

where $dt^r_{P_3} = dt^r + b^r_{P_3}/c$, $dt^s_{P_3} = dt^s + b^s_{P_3}/c$, $N'_3 = (-b^r_{P_3} + b^s_{P_3} + b^r_{\Phi_3} - b^s_{\Phi_3})/\lambda_3 + N_3$.

The receiver clock can be calculated with Eqs. (8) and (9) by Kalman filtering. The time reference of the receiver clock is depending on the IGS products used. For example, the time reference of the GPS PPP time transfer results in BIPM is IGRT, while it changes to be IGST if the IGS Final products are used.

3.2 The Time Reference of the RTS Products

Compared with the IGS Final products, the RTS products have the advantages of low latency of about 30 s [16] and high sampling rates (Table 1). The GPS combined products in IGS01/IGS01 are updated once every 5 s. However, owing to the time reference difference of the RTS products produced from individual analysis centers, the time reference for the combined products will be discontinuous due to the absence of the analysis centers' RTS products, the outliners or the network interruption. The GPS PPP time transfer results will occur a jump resulting from the discontinuity of the time reference, which can be avoided when the IGS post-processed products are used. Figure 4 shows the GPS PPP time transfer results using the RTS products between PTBB and IENG from 2017-09-17 to 2017-09-19.

As shown in Fig. 4, there often occurs clock jumps when carrying out time transfer at PTBB and IENG, which is the same at each epochs. When looking at the difference between the two stations, these jumps cancel. Therefore, the time transfer

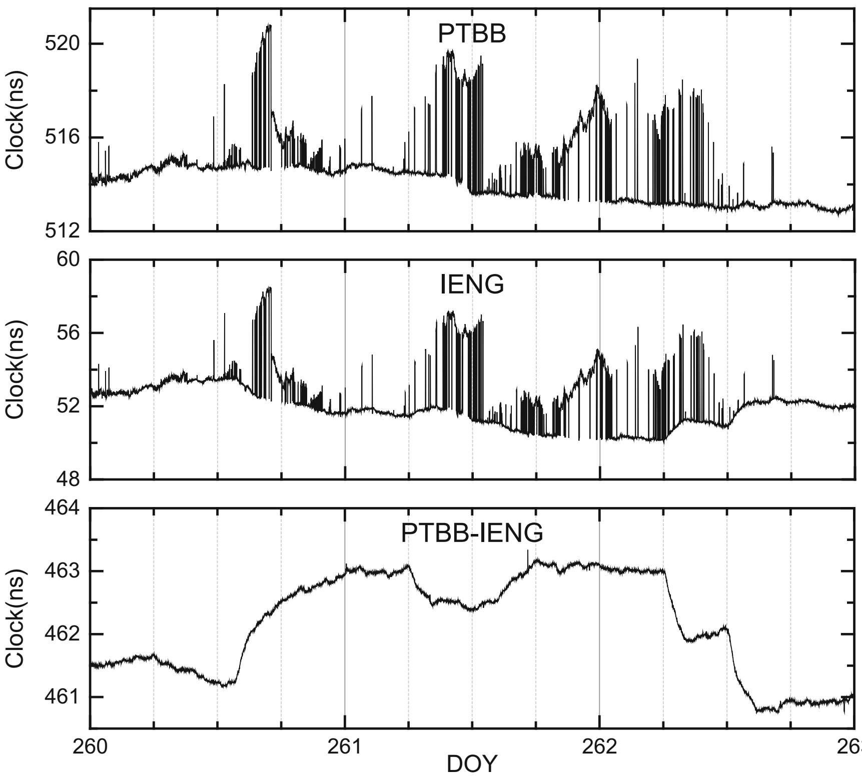

Fig. 4 PPP time transfer solutions between PTBB and IENG

results at a single station by GPS PPP will be damaged resulting from the discontinuity of the RTS products. Fortunately, this effect could be canceled for the time link [17].

3.3 The Experiments

To further analyze and confirm the practicability of the RTS products for subnanosecond level real-time time transfer, we carried out a simulated real-time time transfer experiment between PTBB and BRUX, IENG or OPMT. The observation data which has a total of 16 days from 2017-09-10 to 2017-09-25 is downloaded. The GPS PPP time transfer algorithm is implemented on the modified version of RTKLIB-2.4.3b29 [18]. The precise ephemeris and clocks products are the IGR and the IGC01. The IGC01 is obtained by the same way as Sect. 1.2.2. There are three reasons why the IGS Final products are not used. Firstly, the latency of the IGS Final products is too long, about 12–18 days. Secondly, there hardly exists any differences of the time transfer results no matter which one is used, IGR or IGS Final [9]. Thirdly, it's more comparable when using the IGR for time transfer so as to be in accordance with BIPM. Figure 5 shows the converged time transfer results (150 min later) between PTBB and BRUX, IENG or OPMT. The black curve denotes the IGR, and has been shifted by 0.5 ns. The green curve denotes the PPP (IGC01). The red curve denotes the PPP(IGR), and has been shift by −0.5 ns.

In Fig. 5, we observed that the IGR is better than the PPP(IGR) and the PPP (IGC01). The PPP(IGC01) is almost the same as the PPP(IGR). The clocks at IENG occur a jump about 2 ns. There is no time transfer results in DOY253, DOY254 or DOY260 due to the absences of the observation data at OPMT.

Next, we calculate the accuracies of the PPP time transfer results using different IGS products. Here we take the IGR station clocks as the reference owing to that the accuracy is up to 0.075 ns [7]. Figure 6 shows the clock difference between the PPP (IGC01) or the PPP(IGR) and the IGR. Table 3 summarizes the statistic of difference for the three time links.

As shown in Fig. 6 and Table 3, the time transfer accuracies for the three links are almost the same. The accuracy for the link PTBB-BRUX is the same with that for the link PTBB-OPMT, which is 0.15 ns for the RMS, and 0.12 ns for the STD. The accuracies for the link PTBB-IENG are 0.30 ns for the RMS and 0.24 ns for the STD, they are slightly lower than that for the other two links. This may be related to the jump occurred within DOY261–DOY264.

The time transfer stability is also crucial. Apart from the link PTBB-OPMT for the incompleteness of the observation data or the IGR station clocks, we only calculate the stabilities of the links PTBB-BRUX and PTBB-IENG. The overlapping Allan variance is as follows [18]:

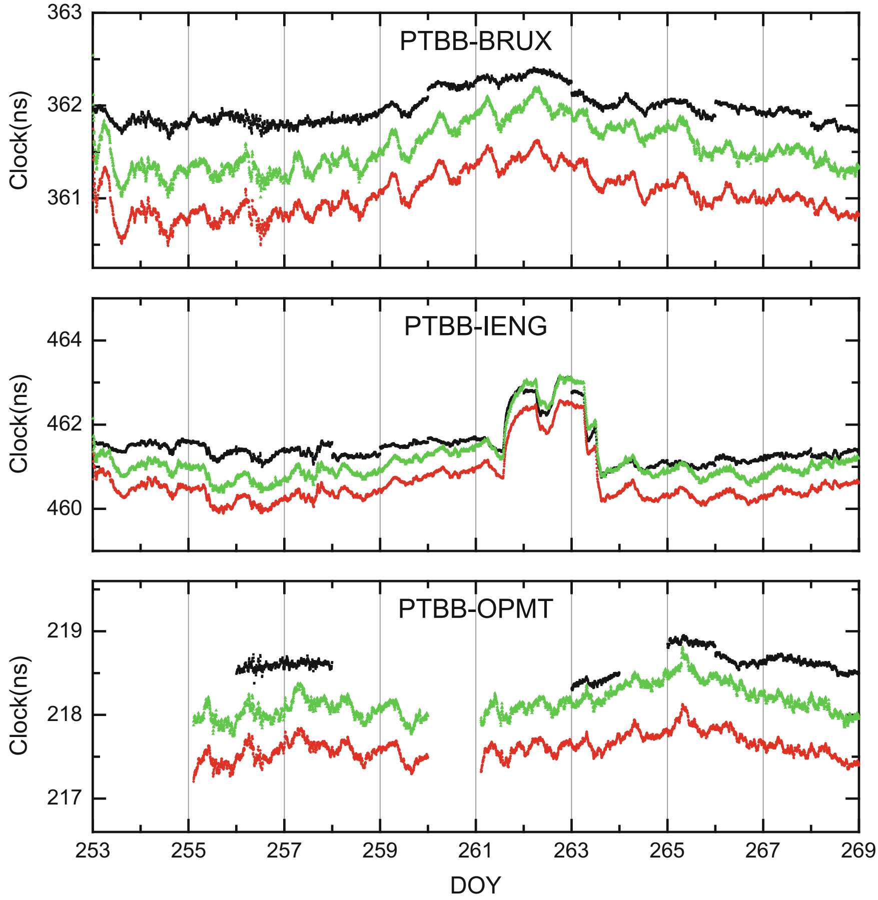

Fig. 5 Time transfer solutions obtained using IGR, PPP(IGC01) and PPP(IGR) (Black: IGR, +0.5 ns. Green: PPP(IGC01). Red: PPP(IGR), −0.5 ns)

$$\sigma_y^2(\tau) = \frac{1}{2(N-2m)\tau^2} \sum_{i=1}^{N-2m} (x_{i+2m} - 2x_{i+m} + x_i)^2 \quad (10)$$

where x_i is the clocks. N is the number of the clocks. $\tau = m\tau_0$, τ_0 is sampling interval of 5 min. Figures 7 and 8 respectively shows the time transfer stabilities of the two links using different IGS products.

As shown in Figs. 7 and 8, the time transfer stability of the IGR is much better than the PPP(IGR), which is almost the same with the PP(IGC01). The stabilities of the PPP(IGC01) for the links PTBB-BRUX and PTBB-IENG are up to 2.0E−15 and 7.5E−15, which not only contain the stabilities of the reference time, but also the stabilities resulting from the time transfer methods, the length of the links and

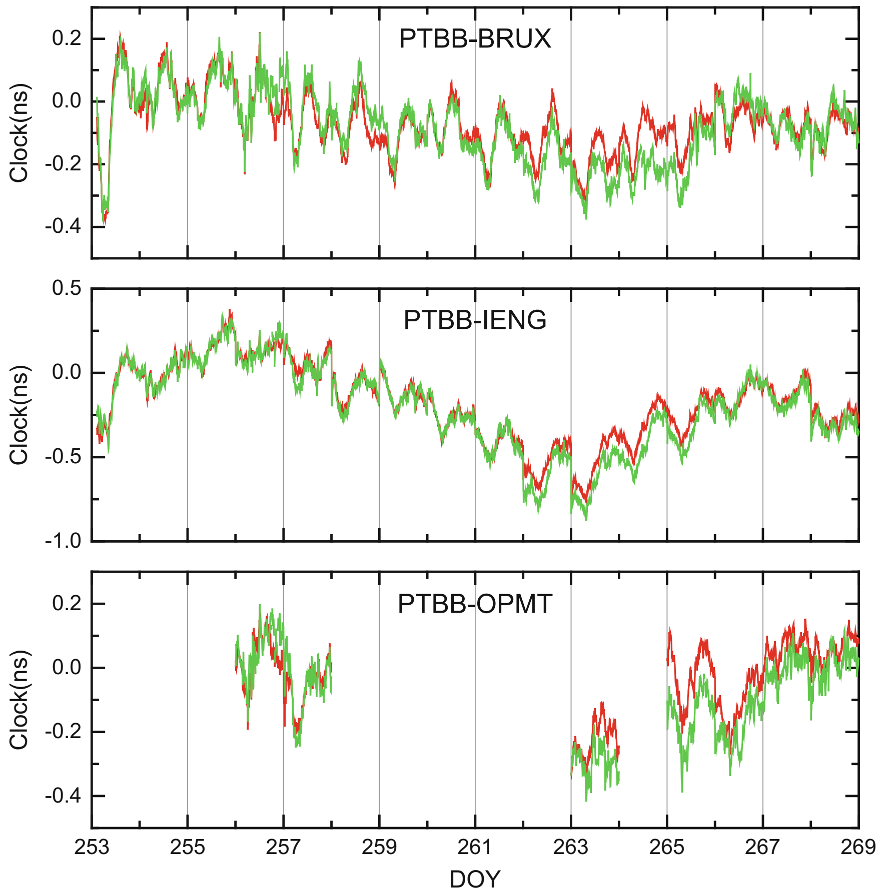

Fig. 6 Difference between the time transfer solutions obtained with PPP(IGC01) or PPP(IGR) with respect to IGR (Green: PPP(IGC01). Red: PPP(IGR))

Table 3 The statistic of difference between the time transfer solutions obtained with PPP(IGC01) or PPP(IGR) with respect to IGR (Unit: ns)

Link	IGS products	Min	Max	Avg.	RMS	STD
PTBB-BRUX	IGR	−0.38	0.22	−0.07	0.12	0.09
	IGC01	−0.38	0.22	−0.08	0.14	0.11
PTBB-IENG	IGR	−0.76	0.38	−0.17	0.28	0.22
	IGC01	−0.88	0.33	−0.21	0.32	0.25
PTBB-OPMT	IGR	−0.36	0.19	−0.04	0.12	0.11
	IGC01	−0.42	0.20	−0.09	0.16	0.13

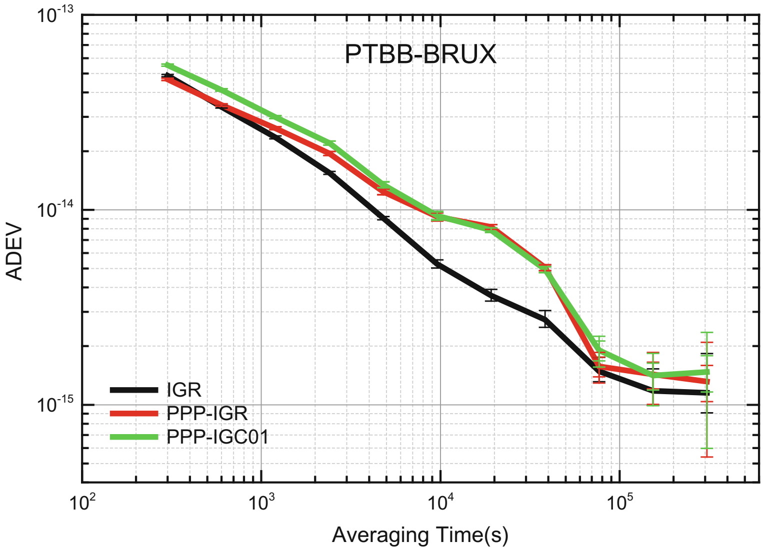

Fig. 7 The time transfer stability between PTBB and BURX

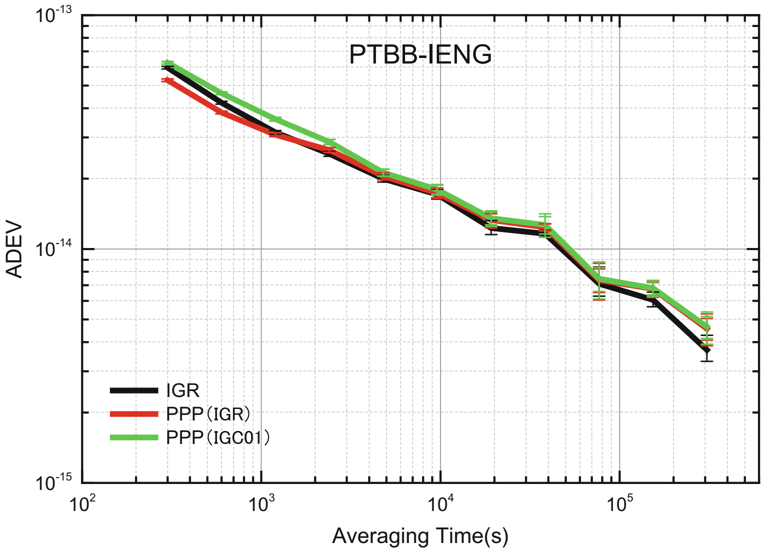

Fig. 8 The time transfer stability between PTBB and IENG

the environments. With the growing of the averaging time, the stability for the link PTBB-BRUX becomes stable, while the stability for the link PTBB-IENG is still decreasing. Combined with Figs. 5 and 6, we can conclude that the low stability for the link PTBB-IENG mainly results from the fluctuation of the reference time at IENG.

4 Conclusion

(1) The accuracy and availability of the RTS products are analyzed. The RMS of the satellite orbit in IGC01 is 33 mm for the radial component, 32 mm for the along-track component and 26 mm for the cross-track component. The STD and the RMS of the satellite 3D-orbit is 20 and 44 mm. The STD and the RMS of the satellite 3D-orbit are respectively 20 and 44 mm. The average availability is about 93.8%.

(2) Focus on the long latency of the GPS PPP time transfer and the low accuracy of the GPS CV time transfer, a real-time subnanosecond level time transfer algorithm using the RTS products was proposed. The time transfer experiment among four time laboratories in Western Europe shows that our algorithm is feasible. The time transfer results show that the accuracy of our algorithm can be reach to 0.30 ns for RMS and 0.25 ns for STD. Moreover, the stability of the time transfer results is up to 2E−15 at 1 day averaging.

(3) The robustness of the real-time time transfer using the RTS products heavily relies on the availability of the RTS products. Interruption of observation data, precise ephemeris missing or network interruption may lead to the failure of time transfer. How to judge and weigh the real-time requirement and how to improve the robustness of the algorithm will be researched next.

Acknowledgements Thanks to the real-time precise ephemeris provided by the IGS RTS analysis center of WUHAN for our experiments. This work is founded by National Natural Science Foundation of China (No. 11403112).

References

1. Petit G, Jiang Z (2008) GPS all in view time transfer for TAI computation. Metrologia 45 (1):35
2. Lewandowski W, Jiang Z (2009) Use of GLONASS at the BIPM. 41st annual Precise Time and Time Interval (PTTI) meeting, pp 5–13
3. Kouba J, Héroux P (2001) Precise point positioning using IGS orbit and clock products. GPS Solutions 5(2):12–28
4. Arias EF (2017) BIPM annual report on time activities. BIPM, Sevres Cedex
5. Ray J, Senior K (2005) Geodetic techniques for time and frequency comparisons using GPS phase and code measurements. Metrologia 42(4):215–232

6. Petit G, Kanj A, Loyer S et al (2015) 1×10^{-16} frequency transfer by GPS PPP with integer ambiguity resolution. Metrologia 52(2):1–4
7. IGS (2007) GPS satellite ephemerides/satellite and station clocks. http://www.igs.org/products. Accessed 12 Dec 2017
8. Xiandong C (2008) Precision time transfer methods based on geodetic time and frequency transfer receivers. J Wuhan Univ (Inf Sci Ed) 33(3):245–248
9. Zhang X, Cai S, Li X et al (2010) Accuracy analysis of time and frequency transfer based on precise point positioning. J Wuhan Univ (Inf Sci Ed) 35(3):274–278
10. Caissy M, Agrotis L (2011) Real-time working group and real-time pilot project. Int GNSS Serv Tech Rep, pp 183–190
11. IGS (2017) Why is IGS involved in real-time GNSS?. ftp://igs.org/pub/resource/pubs/IGS_why_in_RT.pdf. Accessed 12 Dec 2017
12. IGS (2017) IGS real-time service. http://www.igs.org/rts. Accessed Dec 2017
13. Hadas T, Bosy J (2015) IGS RTS precise orbits and clocks verification and quality degradation over time. GPS Solutions 19(1):93–105
14. Elsobeiey M, AI-Harbi S (2016) Performance of real-time precise point positioning using IGS real-time service. GPS Solutions 20(3):565–571
15. BKG (2017) BKG Ntrip client. https://igs.bkg.bund.de/ntrip/download. Accessed 12 Sept 2017
16. IGS (2017) IGS technical report. ftp://igs.org/pub/resource/pubs/2016_techreport.pdf. Accessed Oct 2017
17. Defraigne P, Aerts W, Pottiaux E (2015) Monitoring of UTC (k)'s using PPP and IGS real-time products. GPS Solutions 19(1):165–172
18. RTKLIB (2017) RTKLIB: an open source program package for GNSS positioning. http://www.rtklib.com/. Accessed Sept 2017
19. Riley WJ (2008) Handbook of frequency stability analysis. NIST Special Publication 1065