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Analysis of real-time multi-GNSS satellite products of Wuhan University for rapid response of precise positioning

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Abstract: When users need to quickly process GNSS data, they often need the satellite orbit and clock products with the minimum latency and the highest precision, and it is a good solution to receive the real-time satellite RTCM SSR correction stream to recover the precise satellite orbit and clock products in real time and then store them in an offline repository for rapid response of precise positioning. In this paper, the real-time multi-GNSS orbit and clock RTCM SSR correction stream broadcast by SSRC00WHU0 mountpoint of Wuhan University is used to recover precise satellite orbit and clock products in real time. First, the seven-day orbit files and clock files were obtained and stored locally, and compared with the final MGEX precise satellite orbit and clock products. The results show that the real-time orbit and clock products of GPS and Galileo satellites have the best accuracy, followed by GLONASS satellites and BDS satellites. The real-time orbit products can reach the accuracy level of 5 cm for GPS satellites, 8 cm for Galileo satellites, 15 cm for GLONASS satellites and 16 cm for BDS-3 satellites, and the real-time clock products can reach the accuracy level of 0.43 ns for GPS satellites, 0.44 ns for Galileo satellites, 0.91 ns for GLONASS satellites and 3.14 ns for BDS satellites. Then, the observation data of 20 IGS stations randomly distributed around the world from DOY 150 to 156 in 2021 were processed by static precise point positioning (PPP) mode using the recovered real-time products. The results show that the average positioning accuracy can reach 1.57 cm, 0.76 cm and 1.67 cm in east, north and up direction for static PPP, respectively. Finally, using the recovered real-time products and the final products, the GPS observation data collected in aviation were processed in pseudo real-time in a kinematic mode. The results show that the RMSs of positioning errors are 8.5 cm, 2.4 cm and 16.5 cm in the east, north and up direction, respectively. In addition, one-day multi-GNSS observation data at 20 IGS stations were processed in a kinematic PPP mode, and the results show that the average positioning accuracy is 3.11 cm, 2.04 cm and 4.94 cm in east, north and up directions.

Key words: IGS RTS; precise point positioning; real-time positioning; precise orbit and clock corrections; multi-GNSS

1 Introduction

Precise point positioning (PPP) uses precise satellite orbit and clock products as well the correction model or parameter estimation to eliminate the effects of various related errors, providing global users at an accuracy level of centimeter to millimeter [1][2]. As the precise satellite orbit and clock products provided by International GNSS Services (IGS) usually have some time delays, the production time of the final products can reach up to 13 days, so they are mainly used in the post-processing mode [3][4]. For real-time PPP (RT PPP) users or users who need to process GNSS data quickly, orbit and clock products with lower latency are urgently needed. IGS rapid clocks have a latency of 16 hours and have a sampling rate of only 5 min, which can hardly satisfy the requirement of positioning precision. IGS ultra-rapid products can be obtained in real time, but the prediction accuracy of satellite clock is low at about 3 ns, and the prediction error increases with time, which cannot satisfy the precision requirements either[5]. Therefore, in this case, we urgently need the other orbit and clock products with the minimum latency and the highest precision. It is a good solution to save IGS real-time products in real time and store them in an offline repository.

In order to meet the needs of real-time precise applications, IGS officially launched real-time service (RTS) in 2013[6][7]. The RTS products include Global Navigation Satellite System (GNSS) satellite orbit and satellite clock corrections, which correspond to broadcast ephemeris, broadcast in the form of RTCM (Radio Technical Commission for Maritime Services) state space representation (SSR) correction stream[8]. The RTS products broadcast over the Internet using Networked Transport of RTCM via Internet Protocol (NTRIP) and are available through several analysis centers around the world[5][6]. By receiving the GNSS satellite orbit and clock correction stream and recovering precise orbits and clock in real time with use of broadcast ephemeris, then saving them in an offline repository, users can obtain the highest precision satellite orbit and clock products with minimum latency, and then quickly or even real-time process GNSS data. Hadas et al. [3] examined the availability and latency of real-time correction. The results show that the availability of corrections was beyond 95% for GPS and beyond 90% for GLONASS. XU and YUAN 16] shows that the real-time orbit accuracy of most satellites can reach centimeter level and the real-time clock accuracy can reach sub-nanosecond level except BDS geostationary satellites. Chen et al.[17] shows that hourly static PPP using real-time products provides coordinates with precision of 2~3 cm in the north and 3~4 cm in the east and up components, for any location around the globe, and the precisions of 2.2 cm, 4.2 cm and 6.1 cm are obtained in the north, east, and up directions for the kinematic PPP, respectively. Kazmierski et al.[9] made a comprehensive evaluation of real-time orbit and clock corrections. Elsobeiey and Al-Harbi[6] shows that using IGS RTS products in real-time PPP can improve the position solution root mean square (RMS) by about 50% compared with the solution obtained from the predicted part of the IGS ultra-rapid products.

In this paper, the satellite orbit and clock SSR correction stream broadcast by IGS Analysis Center of Wuhan University is received in real time, and the precise satellite orbit and clock products are recovered in real time, and their integrity and accuracy are analyzed with reference to the final MGEX precise satellite orbit and clock products released by Wuhan University Analysis Center[10]. Using the open source software PRIDE PPP-AR Ⅱ developed by PRIDE Lab research group of Wuhan University[11][12], the observation data from globally distributed IGS stations are processed in static and kinematic PPP models and the aviation data are processed in pseudo real-time kinematic PPP model by using the recovered real-time satellite precise orbit and clock products and final products, respectively. The in real-time PPP accuracy is analyzed to evaluate the performance of the real-time recovered satellite orbit and clock products.

2 Real-time precise satellite orbit and clock products based on SSR correction

2.1 Recovery of precise orbits

The satellite orbit and clock corrections in RTCM-SSR format can be expressed as follows[8]:

$$\Delta_{SSR}(t_0) = (IODE, \delta P_r, \delta P_a, \delta P_c, \delta \dot{P}_r, \delta \dot{P}_a, \delta \dot{P}_c, C_0, C_1, C_2) \quad (1)$$

where t_0 is the Issue of Data (IOD); $IODE$ represents the corresponding broadcast ephemeris used for the calculation of the current orbit and clock corrections; $(\delta P_r, \delta P_a, \delta P_c)$ are the orbital correction components in radial, along-track, and cross-track directions; $(\delta\dot{P_r}, \delta\dot{P_a}, \delta\dot{P_c})$ are the correction rates in radial, along-track, and cross-track directions; (C_0, C_1, C_2) are the polynomial coefficient terms of the real-time satellite clock corrections.

The above satellite orbit corrections are defined in the RAC (radial, along-track, and cross-track) orbital coordinate system. However, the broadcast ephemeris uses the Earth-Centered-Earth Fixed (ECEF) coordinate system. Therefore, the real-time orbit corrections must be converted from the RAC coordinate system to the ECEF coordinate system before it can be applied to the broadcast ephemeris, and then precise satellite coordinates can be obtained[3][6].

For any epoch t, the orbit correction δP in RAC orbital coordinate system at epoch t can be derived by[5]:

$$\delta P = \begin{bmatrix} \delta_r \\ \delta_a \\ \delta_c \end{bmatrix} = \begin{bmatrix} \delta P_r \\ \delta P_a \\ \delta P_c \end{bmatrix} + \begin{bmatrix} \delta\dot{P_r} \\ \delta\dot{P_a} \\ \delta\dot{P_c} \end{bmatrix} (t - t_0) \tag{2}$$

where δ_r, δ_a, and δ_c are the orbital correction components in radial, along-track, and cross-track directions.

Then, compute the transformation matrix R from RAC to ECEF, and the corresponding ECEF orbit corrections is derived by[5]:

$$R = [e_r, e_a, e_c] = \left[\frac{v}{|v|} \times \frac{r \times v}{|r \times v|}, \frac{v}{|v|}, \frac{r \times v}{|r \times v|}\right] \tag{3}$$

$$\begin{bmatrix} \delta_x \\ \delta_y \\ \delta_z \end{bmatrix} = R \begin{bmatrix} \delta_r \\ \delta_a \\ \delta_c \end{bmatrix} \tag{4}$$

where r, v are the satellite position vector and velocity vector computed from the broadcast ephemeris; δ_x, δ_y, and δ_z are the correction components in X, Y, and Z directions in ECEF coordinate system.

Finally, by applying real-time ECEF orbit corrections to broadcast satellite coordinates, the precise satellite orbit coordinates are calculated[5]:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{prec} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{brdc} - \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_z \end{bmatrix} \tag{5}$$

where $(X, Y, Z)_{prec}$ are the precise satellite coordinates in the ECEF coordinate system and $(X, Y, Z)_{brdc}$ are the broadcast satellite coordinates.

It should be noted that there are generally two reference points for satellite position corrections provided in satellite orbit SSR correction stream, the satellite antenna phase center (APC), and the satellite Center of Mass (CoM). If the reference point is the antenna phase center, the satellite antenna phase deviation correction is needed to obtain the satellite centroid coordinates in the ECEF coordinate system. Typically, the reference of the SSR correction stream is indicated in the corresponding information description of the mountpoint that receives the SSR correction stream.

2.2 Recovery of precise clock

At epoch t, precise satellite clock can be calculated by applying satellite clock corrections to broadcast satellite clock[8]:

$$\left.\begin{aligned} \delta C &= C_0 + C_1(t - t_0) + C_2(t - t_0)^2 \\ dt_{prec} &= dt_{brdc} - \frac{\delta C}{c} \end{aligned}\right\} \tag{6}$$

where C_0, C_1, and C_2 are the polynomial coefficient terms of the real-time satellite clock corrections; c is the speed of light in meters per second in the vacuum; dt_{brdc} is the satellite clock computed according to the broadcast ephemeris; dt_{prec} is the precise satellite clock.

3 Quality analysis of real time products

In this study, the SSRC00WHU0 mountpoint of Wuhan University is selected, and the BNC software[13] is used to receive the satellite orbit and clock SSR correction stream in real time. The correction stream provides correction information for GPS, GLONASS, Galileo, BDS and takes CoM as the reference point. The SSR correction stream of 7 days from May 30 to June 5, 2021 is collected in real time. Combined with the broadcast ephemeris, the corresponding precise satellite orbits and clock are recovered and recorded in real time in files in SP3 and CLK format (the interval of both products is 5 s), and these files are stored locally, so as to facilitate the follow-up analysis of the integrity of the real-time correction stream and the accuracy of the recovered precise satellite orbit and clock products.

In this section, the final MGEX products released by Wuhan University Analysis Center is taken as a reference, and the quality of the recovered real-time products is analyzed in terms of integrity, orbit accuracy and clock accuracy.

3.1 Integrity

In practical work, the real-time correction stream will be affected by the stability of the data source itself, the transmission network and the receiving software. Therefore, data of some epochs in the recovered real-time products will be missed. Taking each satellite as a unit, we statistically analyze the integrity of the recovered real-time products for 7 consecutive days from May 30 to June 5, 2021. The integrity rate of a satellite is defined as:

$$\alpha = \frac{m_{available}}{m_{theoretical}} \qquad (7)$$

where $m_{available}$ is the total number of epochs of the satellite's data actually contained in the product; $m_{theoretical}$ is the total number of epochs of the satellite's data theoretically contained in the product. For example, if the interval of the correction stream is 5 s, then the $m_{theoretical}$ for one day should be $86400/5 = 17280$ epochs.

Table 1 shows the data integrity rate of real-time products. As can be seen from Table 1, the satellite data during the experimental period are relatively complete, and the real-time products record the orbit and clock information of 113 GPS/GLONASS/Galileo/BDS satellites. It should be noted that the recovered real-time precise satellite products do not include all satellites of all systems, because there is no corresponding information of those satellites in Table 1 in the real-time SSR correction stream during the test.

Among the satellites in Table 1, the integrity rate of 111 satellites (98% of the total) is more than 70%; the integrity rate of the remaining two satellites (R09 and R15) is very low, which is 13.10% and 19.40%, respectively, mainly because the analysis center broadcasts only a small amount of real-time SSR correction information for these two satellites during the experimental period. The integrity rate of 100 satellites (88% of the total) is more than 80%. The integrity rate of 69 satellites (61% of the total) is more than 90%, with a maximum of 96.77%. From the point of view of different systems, the average integrity rate of GPS satellites is 94.27%. By contrast, the average integrity rate of GLONASS satellites is only 81.64%, which is mainly caused by the particular impact of R15 and R09 satellites during the period. The average integrity rate of Galileo satellites is 92.97%. The average integrity rate of BDS satellite is 85.38%. For BDS satellites, it is worth noting that there are obvious differences between BDS-2 and BDS-3 satellites. The average integrity rate of the BDS-2 satellites is 91.44%. By contrast, the average integrity rate of the BDS-3 satellites is only 82.01%. The average integrity rate of the BDS-3 satellites is about 10% lower than that of the BDS-2. Generally speaking, the integrity of the GPS and Galileo satellites is the best, followed by the BDS satellites, and the integrity of the GLONASS satellites is the worst.

3.2 Accuracy of real-time precise orbits

Taking the final MGEX precise orbit products released by Wuhan University Analysis Center as a reference, the accuracy of the real-time orbit products in SP3 format on 7 consecutive days is analyzed and evaluated. Since the data interval of the final orbit products is 15 minutes whereas the data interval of the real-time orbit products is 5s, in order to avoid additional errors caused by data interpolation, only the data at the same epoch for the final products and the real-time products are compared, and the RMS (root mean square) values of the orbit differences in along-track, cross-track and radial directions for each satellite during the experimental period are calculated according to formula (8), so as to represent the accuracy of real-time satellite orbit products[5]:

Table 1 Satellite data integrity rate of real-time products

PRN	Integrity rate %	PRN	Integrity rate %	PRN	Integrity rate %	PRN	Integrity rate %	PRN	Integrity rate %
G01	93.89	G27	94.06	E01	93.38	C05	93.31	C34	83.26
G02	94.68	G28	94.77	E02	93.01	C06	92.39	C35	78.78
G03	95.53	G29	96.77	E03	93.65	C07	92.47	C36	84.06
G04	96.10	G30	94.60	E04	93.12	C08	95.70	C37	82.71
G05	95.81	G31	95.74	E05	94.77	C09	95.92	C38	76.38
G06	92.89	G32	93.85	E07	93.85	C10	90.92	C39	80.71
G07	92.86	R01	89.95	E08	94.64	C11	90.23	C40	78.72
G08	94.20	R02	89.90	E09	92.03	C12	85.32	C41	74.61
G09	95.23	R03	89.26	E11	90.09	C13	93.39	C42	71.87
G10	95.35	R04	90.43	E12	91.25	C14	91.92	C43	73.54
G12	89.49	R05	90.61	E13	95.05	C16	93.51	C44	71.71
G13	94.58	R07	89.53	E15	92.63	C19	84.50	C45	70.08
G14	94.39	R08	89.17	E19	91.90	C20	85.36	C46	73.79
G15	95.86	R09	13.10	E21	94.56	C21	87.18		
G16	95.86	R12	88.50	E24	91.32	C22	85.13		
G17	95.31	R13	87.50	E25	92.84	C23	88.27		
G18	95.44	R14	90.07	E26	93.85	C24	88.35		
G19	96.11	R15	19.40	E27	93.84	C25	87.91		
G20	95.63	R16	90.54	E30	93.21	C26	87.73		
G21	93.31	R17	89.61	E31	91.62	C27	89.13		
G22	79.34	R18	89.62	E33	91.79	C28	90.95		
G23	95.01	R19	90.25	C01	96.65	C29	87.07		
G24	94.24	R20	84.42	C02	89.66	C30	85.59		
G25	95.59	R21	88.86	C03	74.62	C32	81.94		
G26	95.79	R24	90.50	C04	95.59	C33	84.83		

$$RMS = \sqrt{(\sum_{i=1}^{n} {\Delta_i}^2)/n} \quad (8)$$

where Δ_i is the orbit difference of the epoch i; n is the number of all epochs.

Figures 1 ~ 3 show the RMS differences of along-track, cross-track and radial directions for the GPS, GLOANSS and Galileo satellite orbits between the real-time products and the final products within 7 days. As can be seen from figure 1, the accuracy of the GPS real-time orbit is mostly lower than 5 cm in three directions, however, the accuracy of G14 satellite is slightly larger with an along-track error of 8.20 cm. At the same time, it can also be found that the along-track accuracy of the GPS real-time orbit is slightly worse than the cross-track and radial accuracies. As can be seen from figure 2, except for R09 and R20 satellites, the orbit accuracy of most GLONASS satellites in real-time products is lower than 15 cm in three directions, and the cross-track orbital accuracy of most GLONASS satellites is the highest in the three directions. It can be seen from figure 3 that, similar to GPS, the real-time orbit of Galileo has the characteristics that the accuracy is the best in the radial direction, and the worst in the along-track direction. The real-time orbit accuracy of most Galileo satellites is within 8 cm in the along-track direction, within 6 cm in the cross-track direction, and within 4 cm in the radial direction.

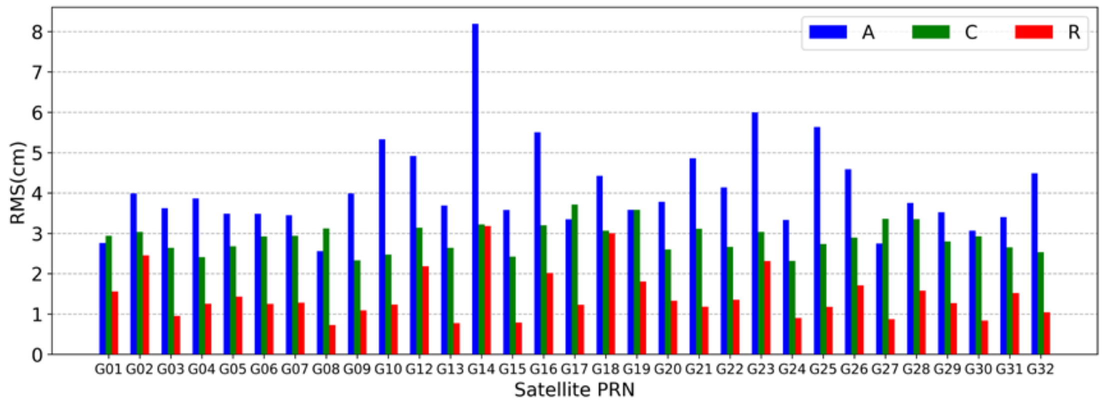

Fig.1 Along-track (A), Cross-track (C) and Radial (R) accuracy of GPS satellite orbit of real-time products

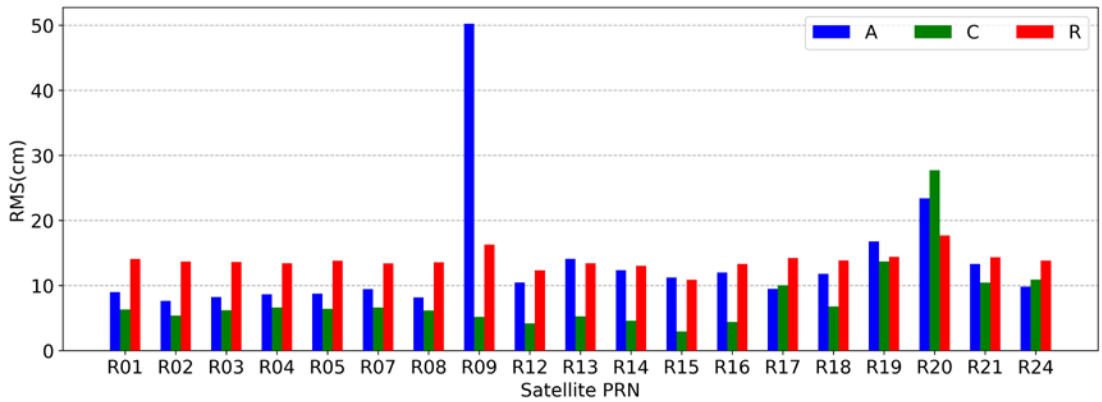

Fig.2 Along-track (A), Cross-track (C) and Radial (R) accuracy of GLONASS satellite orbit of real-time products

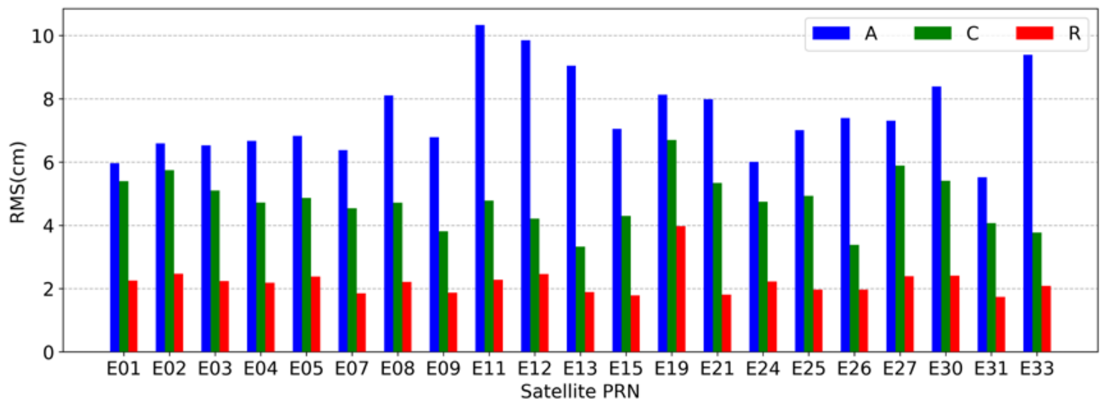

Fig.3 Along-track (A), Cross-track (C) and Radial (R) accuracy of Galileo satellite orbit of real-time products

Figures 4 and 5 show the RMS differences of along-track, cross-track and radial directions for the BDS Geostationary Earth Orbit (GEO) and BDS inclined geosynchronous orbits (IGSO) / medium Earth orbit (MEO) satellite orbits between the real-time products and the final products within 7 days, respectively. It should be noted that in figure 5, the IGSO/MEO satellites are divided into two parts for display according to the attributes of BDS-2 and BDS-3. At the same time, the GEO satellites in figure 4 are all BDS-2 satellites, so it is convenient to find the difference between BDS-2 and BDS-3 satellites. As can be seen from figures 4 and 5, during the experimental period, the real-time orbit accuracy of the BDS GEO satellite is generally low, which is the worst among all systems. Generally, it has meter-level accuracy in the cross-track and radial directions, and even up to more than ten meters in the along-track direction. The real-time orbit accuracy of the BDS IGSO/MEO satellites is significantly improved compared with the GEO satellites, most IGSO/MEO satellites can reach an accuracy level within 20 cm, which is similar to that of GLONASS satellites, but the along-track accuracy of some satellites is poor, exceeding 30 cm.

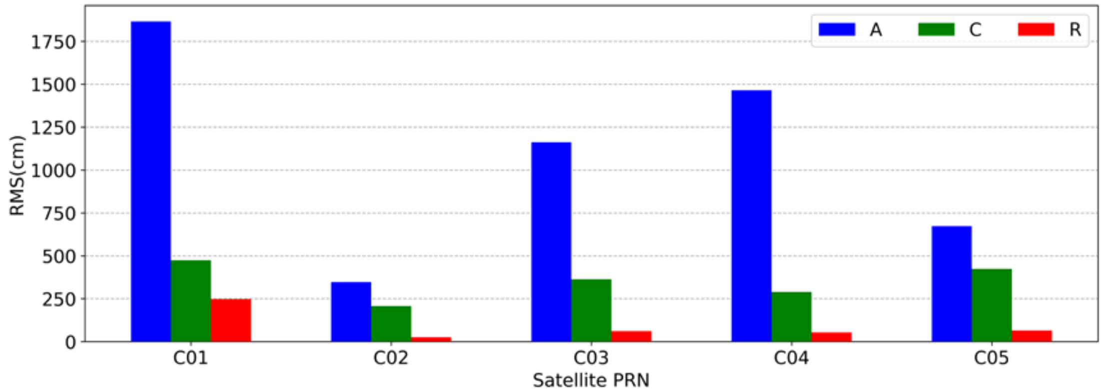

Fig.4 Along-track (A), Cross-track (C) and Radial (R) accuracy of BDS GEO satellite orbit of real-time products

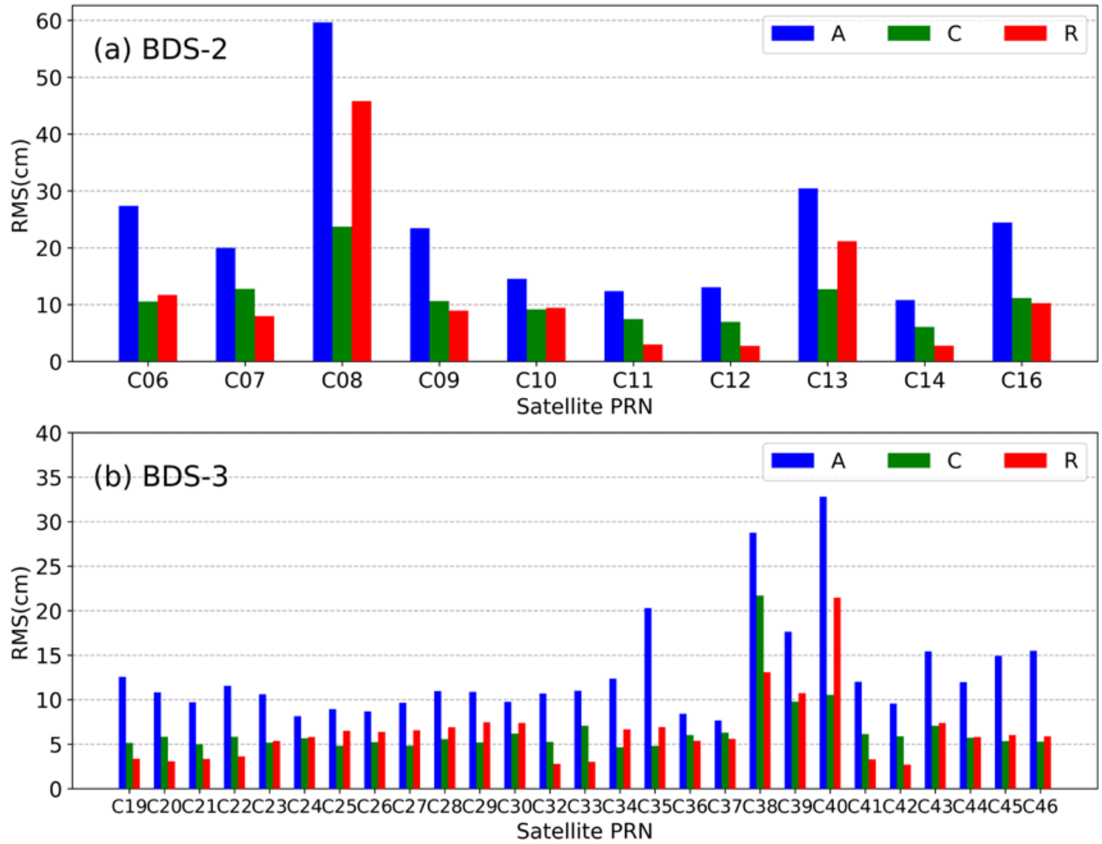

Fig.5 Along-track (A), Cross-track (C) and Radial (R) orbital accuracy of BDS IGSO/MEO satellites for real-time products. (It is divided into two parts: **a** BDS-2, **b** BDS-3)

The real-time orbit accuracy of BDS-3 satellites is much higher than that of BDS-2 satellites. The average orbital accuracy of all BDS-2 satellites in the along-track, cross-track and radial directions is 383.22 cm, 124.63 cm and 38.46 cm, which is mainly caused by the poor accuracy of GEO satellites. The average accuracy of all BDS-3 satellites in the along-track, cross-track and radial directions is 13.01 cm, 6.52 cm and 6.39 cm, which is 97%, 95% and 83% higher than those of BDS-2 satellites in the along-track, cross-track and radial directions, respectively. Even if the BDS-2 GEO satellites are not considered in the accuracy statistics, the average RMS values of the remaining BDS-2 satellites in the along-track, cross-track and radial directions are 23.61 cm, 11.12 cm and 12.38 cm, which are 1.8, 1.7, 1.9 times larger than those of the BDS-3 satellites, respectively. In fact, the real-time orbit accuracy of the BDS-2 satellite is still worse than that of the BDS-3 satellites. Overall, the real-time BDS orbit accuracy still has a great room for improvement.

Table 2 shows the average RMS differences between the real-time orbits and the final orbits of satellites of different systems during the experimental period. It can be seen from Table 2 that the real-time orbit accuracy of GPS satellites is the highest among all systems, and its average accuracy in the along-track, cross-track and radial directions is 4.10 cm, 2.89 cm and 1.46 cm, respectively. The average accuracy of Galileo satellites in the along-track, cross-track and radial directions is 7.49 cm, 4.75 cm and 2.21 cm, respectively, which is only slightly worse than that of GPS satellites. It has the second-best orbit accuracy among all systems. Both GPS and Galileo satellites have the best real-time orbit accuracy in the radial direction, and the worst in the along-track direction. Next are the BDS IGSO/MEO and GLONASS satellites, whose real-time orbit accuracy is equivalent in the along-track and cross-track directions. In the radial direction, the BDS IGSO/MEO satellites perform better than the GLONASS satellites. Finally, the average accuracy of the BDS GEO satellites in the along-track, cross-track and radial directions is 1102.42 cm, 351.65 cm and 90.62 cm, respectively, which is the worst.

3.3 Accuracy of real-time precise clocks

Similarly, the real-time clock products in CLK format for 7 consecutive days is compared with the final MGEX precise clock products released by Wuhan University Analysis Center to analyze its accuracy. Because the clock products generated by different analysis centers use different reference clocks, there is a systematic deviation between the clock products. In this paper, the quadratic difference method is used to calculate the accuracy of the real-time precise clock. Firstly, one of the satellites of each system is selected as a reference satellite (in this paper, G01, R01, E01 and C01 are selected, respectively). Then, the other satellites make a difference with the reference satellite clock at the same epoch of the real-time clock product and the final clock product, thus eliminating the impact of different reference clocks. Then make a second-order difference between the first-order difference results of the real-time product and the final product. Finally, the formula (9) is used to calculate the RMS value of the quadratic difference to represent the accuracy of the real-time clock products[5]:

Table 2 Average orbit accuracy of satellites for different systems in real-time products

Satellite system	Average accuracy in different directions (cm)		
	Along-track	Cross-track	Radial
GPS	4.10	2.89	1.46
Galileo	7.49	4.75	2.21
BDS IGSO/MEO	15.88	7.76	8.00
GLONASS	13.43	7.90	13.86
BDS GEO	1102.42	351.65	90.62

$$RMS = \sqrt{\sum_{i=1}^{n}(\Delta_i - \bar{\Delta})^2/n} \quad (9)$$

where Δ_i is the quadratic difference of the epoch i of each satellite; $\bar{\Delta}$ is the mean value of the quadratic difference sequence of each satellite clock; n is the number of epochs.

Figure 6 shows the RMS values calculated according to formula (9) for GPS, GLOANSS, Galileo and BDS real-time precise satellite clock over a 7-day period. It can be seen from figure 6 (a) that there are obvious differences in real-time clock accuracy among different GPS satellites. Most GPS satellites can achieve an accuracy level better than 0.6 ns, and the best accuracy is 0.15 ns (G19), but the accuracy of G08/G09/G10/G25/G27/G28 satellites is obviously poor, and the worst accuracy is only 0.90 ns (G08). Overall, the average real-time clock accuracy of all GPS satellites is 0.43 ns, which is the highest among all satellites of all constellations. As can be seen from figure 6 (b), the real-time clock accuracy of each satellite of GLONASS system is very close. The real-time clock accuracy of GLONASS satellites basically fluctuates between 0.8~1.0 ns. The best accuracy is 0.59 ns (R15), and the worst is only 1.14 ns (R20). The average real-time clock accuracy of all GLONASS satellites is 0.91 ns. As can be seen from figure 6 (c), the real-time clock accuracy of Galileo satellites is relatively higher. Except for the poor accuracy of E04 and E11 satellites, which are 0.89 and 0.83 ns, respectively, the other satellites can achieve an accuracy level of better than 0.6 ns. The average accuracy of all Galileo satellites is 0.44 ns, which is similar to GPS satellites. It can be seen from Figure 6 (d) that the real-time clock accuracy of the BDS satellites is relatively poor compared with the other systems. For about 54% of the BDS satellites, their clock accuracy is more than 3 ns. The worst accuracy is 6.76 ns (C30), and the best accuracy is only 1.25 ns (C09), which is relatively poor compared with the other systems. The average real-time clock accuracy of BDS is only 3.45 ns, which is much worse than that of the other constellation satellites. Unlike the orbit, there is no significant difference in the clock accuracy between the BDS GEO and IGSO/MEO satellites, and between the BDS-2 and BDS-3 satellites, which may be due to the quadratic difference method that eliminates the systematic deviation.

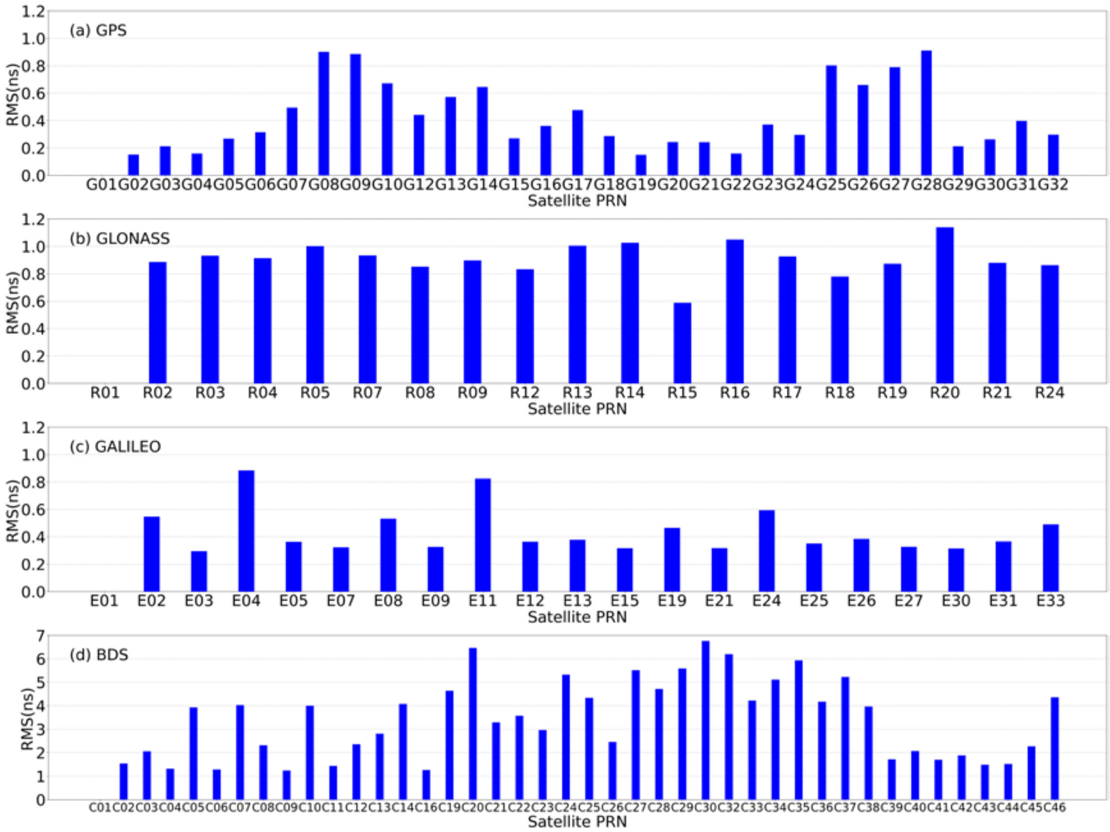

Fig.6 Accuracy of satellite clocks of real-time products for **(a)** GPS, **(b)** GLONASS, **(c)** Galileo, **(d)** BDS. (Due to the poor accuracy of BDS satellites, the scale of y-axis in **d** subplot is different from that in **a**, **b** and **c** subplots)

On the whole, during the experimental period, the real-time clock accuracy of GPS and Galileo satellites is relatively higher, followed by GLONASS satellites. Taking the final products as a reference, their accuracy can reach the sub-nanometer level, which is much higher than that of the IGS ultra-rapid products. It should be noted that the BDS satellites only have the accuracy of a few nanoseconds, and its real-time clock accuracy is the worst.

4 The application of real-time products in RTPPP

The real time precise satellite orbit and clock products are mainly used in real-time PPP (RTPPP), to achieve rapid response to GNSS data processing. Therefore, this section indirectly verifies the quality and application effect of the real-time products through static and pseudo-real-time kinematic PPP. The open source PPP GNSS data processing software PRIDE PPP-AR Ⅱ developed by Prof. Jianghui Geng (Songfeng Yang, etc.) of GNSS Research Center of Wuhan University is used in the test[18]. The software can support GPS, GLONASS, Galileo, BDS-2/3 and QZSS processing, handle high-frequency data up to 50Hz in a variety of processing modes. The software can be applied to large dynamic mobile platforms, and has good positioning and application performance.

Table 3 Test setup and data processing strategies

Items	Models/Strategies
Processing mode	Static;
	Kinematic;
Constellations	GPS/GLONASS/Galileo/BDS;
Observations	Ionospheric-free linear combination code and carrier-phase measurements;
Priori noise	Pseudorange: 0.3 m;
	Carrier-phase: 0.01 cycles;
Elevation cutoff angle	7°
Data interval	Static: 30 s;
	Kinematic: 0.5 s, 30 s;
Precise satellite orbits and clocks	Real-time products derived from real-time stream: SSRC00WHU0 (CoM) + broadcast ephemeris;
	Final MGEX products released by Wuhan University Analysis Center;
Code biases	Using CODE’s DCB products to correct the satellite-end P1C1 and P2C2 differential code biases (DCB)
Receiver antenna phase center	PCO and PCV values from igs14.atx file
Tidal displacements	Corrected by IERS Convention 2010
Relativistic effect	Corrected
Phase windup	Corrected
Station coordinates	Static: Estimated as a constant value for one day;
	Kinematic: Estimated as white noise;
Receiver clocks	Estimated as white noise, one value for each GNSS system
Zenith tropospheric delay	Mapping function: Global Mapping Function (GMF)[14]
	Saastamonien model[15] + Estimated as piece-wise constant
Horizontal troposphere gradients	Estimated as piece-wise constant
Ionosphere delays	First-order ionosphere delay is eliminated using the ionosphere-free combination; Higher-order ionosphere delay is corrected using the CODE global ionosphere maps
Phase ambiguities	Float constants for each continuous arc

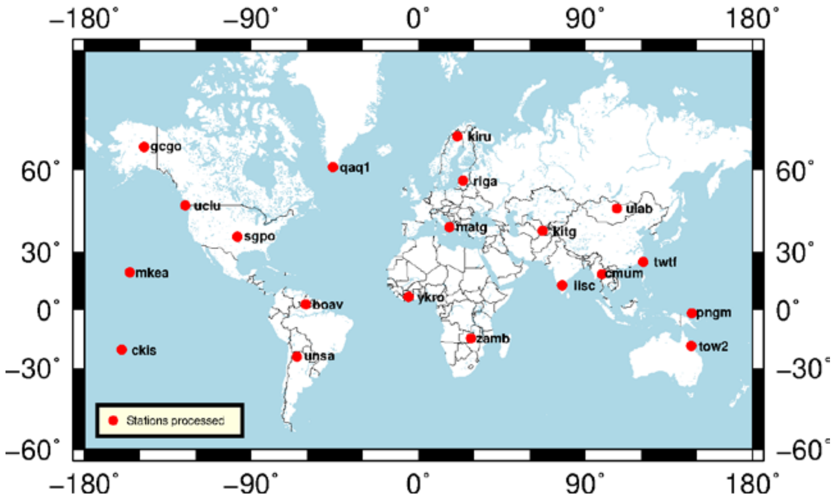

Fig.7 IGS stations used for static test

4.1 Static test

As shown in figure 7, 20 globally distributed IGS stations are randomly selected to conduct static PPP processing using the daily observation data from May 30th to June 5th (DOY 150~156) in 2021. The specific processing strategies in the test are shown in the static mode section in Table 3. At the same time, as a reference, keeping all other processing strategies unchanged, this section also uses the final MGEX orbit and clock products released by Wuhan University Analysis Center to process the same observation data in the static PPP mode.

In this study, the weekly combination coordinates provided by IGS are used as reference coordinates, the difference between the daily solution of static PPP at each station and the corresponding reference coordinate is calculated, and is converted to the ENU (east, north, and up) coordinate directions to get the positioning error which is used to evaluate the positioning accuracy. Figures 8 and 9 show the RMS of the positioning errors using the final products and the real-time products during the 7 days of the test, respectively. It can be seen from Figure 8 that for the static PPP using the final products, the daily float solution of most stations can achieve the accuracy of better than 6.0 mm in the east and north directions and better than 1.0 cm in the up direction. The positioning accuracy at CMUM station in the up direction is slightly worse than that of other stations, which is 1.02 cm. In general, the positioning accuracies in the east and north directions are comparable, and better than that in the up direction. As can be seen from Figure 9, for the static PPP using real-time products, the positioning accuracy of the corresponding daily float solution is slightly worse than that of the final products, but most stations can achieve the accuracy of better than 2.0 cm in the east and north direction and better than 3.0 cm in the up direction. The positioning accuracy in the east direction of YKRO and ZAMB station is slightly worse than other stations.

Table 4 shows the specific RMS of the positioning errors in the direction of east, north and up at each station. It can be seen from Table 4 that using the final products for static PPP processing, the results are in good agreement with the IGS weekly combination solution. The optimal positioning accuracy can reach 1.0 mm in east direction, 0.7 mm in north direction and 2.2 mm in up direction. The average positioning accuracy in east, north and up directions is 0.26 cm, 0.29 cm, 0.53 cm, respectively. In contrast, the positioning accuracy of the results using real-time products is slightly lower. The optimal positioning accuracy in east, north and up directions is 6.6 mm, 3.0 mm and 6.2 mm, respectively, and the average positioning accuracy in east, north and up directions is 1.57 cm, 0.76 cm, 1.67 cm, respectively. Overall, the positioning accuracy at each station is comparable, the positioning accuracy in north direction is the best, and the worst in up direction.

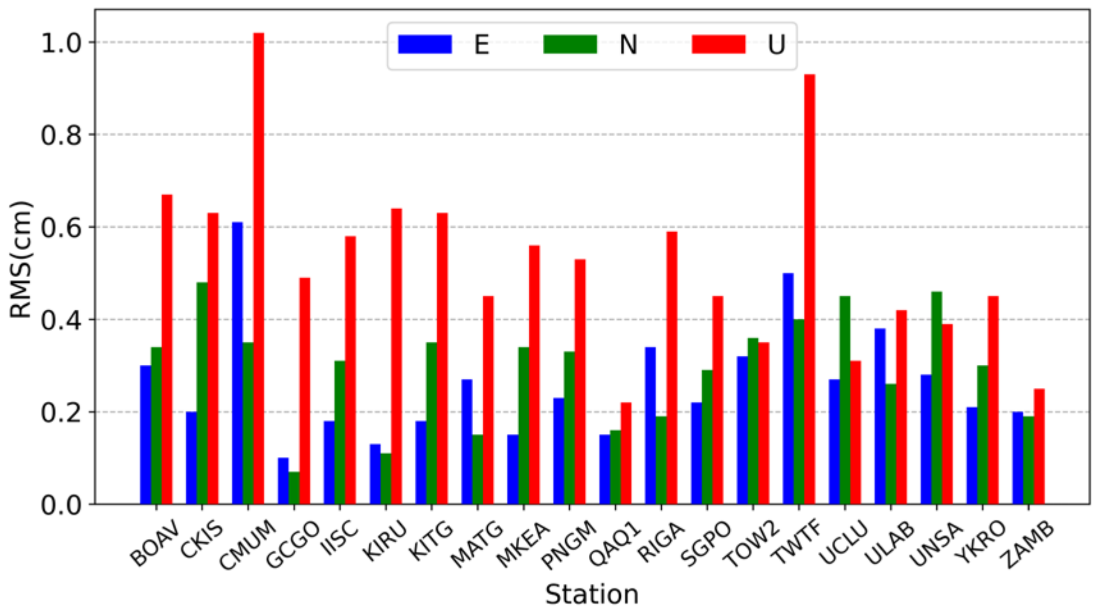

Fig.8 The RMS of the positioning errors using the final products in static PPP test

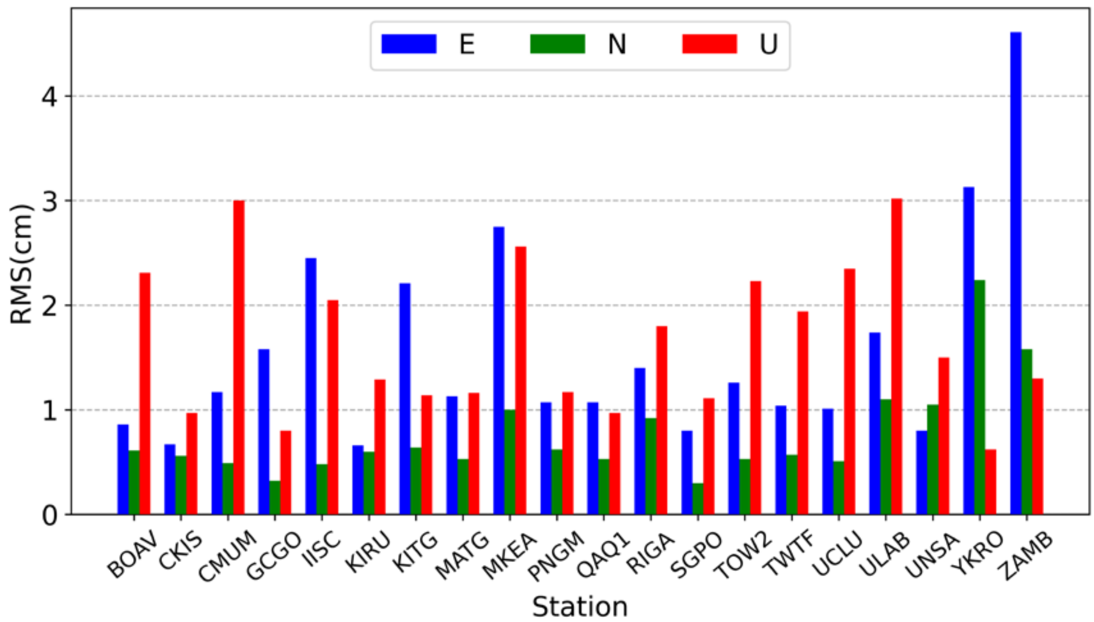

Fig.9 The RMS of the positioning errors using the real-time products in static PPP test

4.2 Kinematic test

In the kinematic test, firstly, this study indirectly verifies the application effect of real-time products by pseudo real-time kinematic PPP processing using GPS observation data collected in aviation. In this test, the aircraft mainly flew in the northeast of Hainan Province in China. The flight trajectory is shown by the red solid line in Fig. 10, in which the red triangle represents the reference station. The test was carried out on May 29, 2021. The observation time is about 3.5 hours and the data sampling rate is 0.5 seconds. The specific processing strategy in the test is shown in the kinematic mode section in Table 3. The processing mode of PRIDE PPP-AR Ⅱ software is set to kinematic mode, and the final products released by Wuhan University Analysis Center and real-time products are used to process the GPS observation data respectively while the other settings are kept the same, and the corresponding kinematic positioning results are obtained.

Table 4 Comparison of positioning accuracy between using final products and real-time products

Station	Final MGEX products RMS (cm)			Real-time products RMS (cm)		
	East	North	Up	East	North	Up
BOAV	0.30	0.34	0.67	0.86	0.61	2.31
CKIS	0.20	0.48	0.63	0.67	0.56	0.97
CMUM	0.61	0.35	1.02	1.17	0.49	3.00
GCGO	0.10	0.07	0.49	1.58	0.32	0.80
IISC	0.18	0.31	0.58	2.45	0.48	2.05
KIRU	0.13	0.11	0.64	0.66	0.60	1.29
KITG	0.18	0.35	0.63	2.21	0.64	1.14
MATG	0.27	0.15	0.45	1.13	0.53	1.16
MKEA	0.15	0.34	0.56	2.75	1.00	2.56
PNGM	0.23	0.33	0.53	1.07	0.62	1.17
QAQ1	0.15	0.16	0.22	1.07	0.53	0.97
RIGA	0.34	0.19	0.59	1.40	0.92	1.80
SGPO	0.22	0.29	0.45	0.80	0.30	1.11
TOW2	0.32	0.36	0.35	1.26	0.53	2.23
TWTF	0.50	0.40	0.93	1.04	0.57	1.94
UCLU	0.27	0.45	0.31	1.01	0.51	2.35
ULAB	0.38	0.26	0.42	1.74	1.10	3.02
UNSA	0.28	0.46	0.39	0.80	1.05	1.50
YKRO	0.21	0.30	0.45	3.13	2.24	0.62
ZAMB	0.20	0.19	0.25	4.61	1.58	1.30
Average	0.26	0.29	0.53	1.57	0.76	1.67

Fig.10 The flight trajectory of the aircraft in the kinematic test

In order to evaluate the positioning accuracy of the kinematic positioning results, this study uses the RTKLIB software to process the experimental data using kinematic relative positioning mode, and the integer ambiguity resolution is set to "fix and hold" to obtain the fixed solution (the reference station is located near Qionghai City, Hainan, and the maximum baseline length is up to 100 km). Taking the relative positioning results output by RTKLIB as the reference results (with the increase of baseline length, the positioning accuracy of reference results may decrease), the positioning error is obtained by calculating the difference between the kinematic PPP float positioning results of the final/real-time products and the reference results in ENU coordinate system.

Fig. 11 shows the time series of the position difference between the kinematic PPP float positioning result and the reference result in the directions of east, north and up. The blue curve represents the position errors using the final products, and the orange curve represents the position errors using the real-time products. It can be seen from Figure 11 that the two time series are very consistent with each other. The RMS of the position errors between the kinematic PPP positioning results based on the final products and the reference results are 8.08 cm, 2.09 cm and 17.86 cm, respectively, in the east, north and up directions. The RMS of the position errors between the kinematic PPP positioning results based on the real-time products and the reference results are 8.53 cm, 2.41 cm and 16.47 cm, respectively, in the east, north and up directions. Only the GPS observation data were processed in this aviation test. Through the research and analysis of the quality of the real-time products in the previous sections, compared with the final products, the average accuracy of the real-time GPS orbits is better than 5 cm, and the average accuracy of the real-time GPS clock is 0.43 ns. It can be considered that the real-time GPS products is actually very close to the final products, so the “Rt” positioning result is also very close to “Fin”. This indirectly proves that the real-time GPS precise satellite orbit and clock products recovered by SSR correction stream have relatively high accuracy, and it can also achieve the similar positioning accuracy as the final products when it is used by users. The above results also fully demonstrate the advantages and potential of the solution of real-time recovery of precise satellite orbit and clock products and storing them in an offline repository, that is, users can use these products to process GNSS data with minimum latency or even real-time without waiting for the release of the IGS final products. At the same time, they can also obtain the positioning results with an optimal accuracy of the centimeter level.

In addition, because only GPS data are collected in the above aviation test, in order to fully verify the quality of GPS, GLONASS, Galileo and BDS satellites in real-time products, this study uses 20 IGS stations as shown in the Section 4.1 and uses PRIDE PPP-AR II software to process the GPS, GLONASS, Galileo and BDS observation data of all stations on DOY 154, 2021 using kinematic PPP mode. Similarly, as a comparison, the final MGEX products of Wuhan University and real-time products were used in the test. Figure 12 selects the TWTF station and shows the difference of the time series in the east, north and up directions between the results obtained by using the final products and real-time products and the reference coordinates. As can be seen from Figure 12, the positioning accuracy of using the real-time products is slightly worse than that of using the final products, and the RMS values of the kinematic solution differences in the east, north and up directions are 1.67 cm, 1.66 cm and 3.94 cm, respectively, which are slightly higher than the corresponding RMS values of the final products. Table 5 shows the RMS values of the sequence of differences between the kinematic solutions and the reference coordinates obtained by using the final products and real-time products of all stations in the east, north and up directions. It can be seen from Table 5 that the kinematic solutions obtained by using the final products have very high positioning accuracy, and the corresponding RMS values of the kinematic solution in east, north and up directions of each station are smaller than those of the kinematic solutions obtained by using the real-time products. The average positioning accuracy of the kinematic solutions of all stations obtained by using final products in east, north and up directions is 0.88 cm,0.89 cm and 2.23 cm, respectively. The kinematic solutions obtained by using the real-time products generally have the accuracy levels of centimeters in horizontal directions and centimeters to decimeters in vertical direction. The average positioning accuracy of kinematic solutions obtained by using real-time products in east, north and up directions is 3.11 cm, 2.04 cm and 4.94 cm, respectively. Although this level of positioning accuracy is slightly lower than that of the final products, it can still meet the requirements of positioning accuracy in near real-time applications that require rapid PPP processing (usually within a few hours).

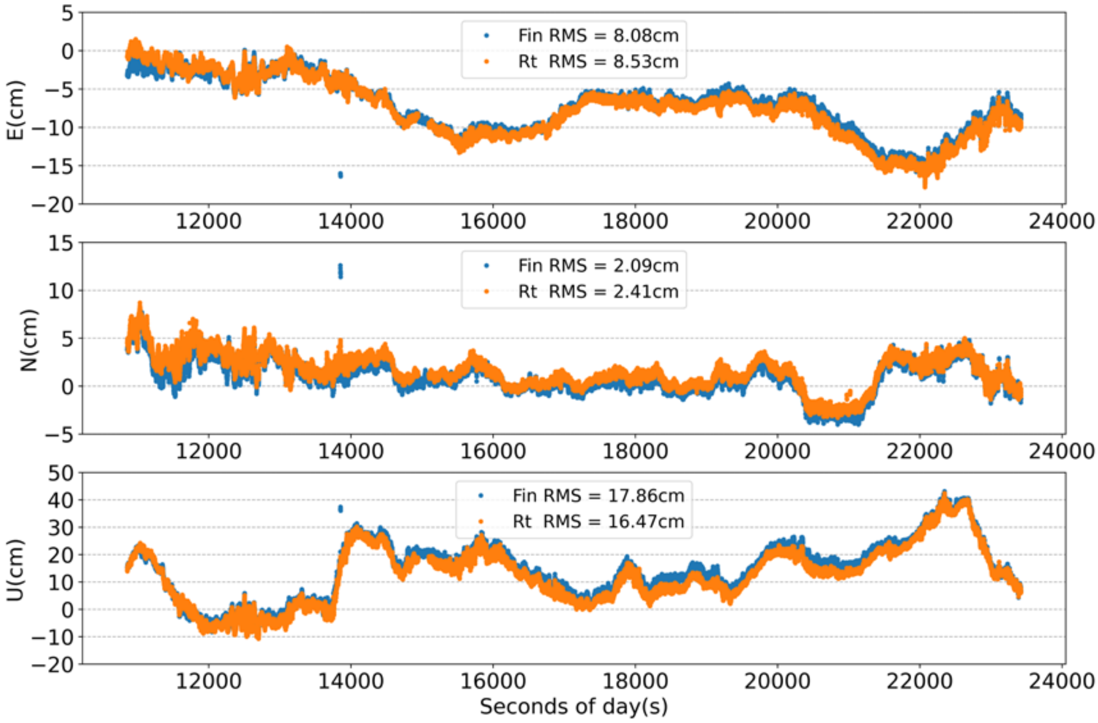

Fig.11 Position difference between the kinematic PPP float positioning results and the reference result

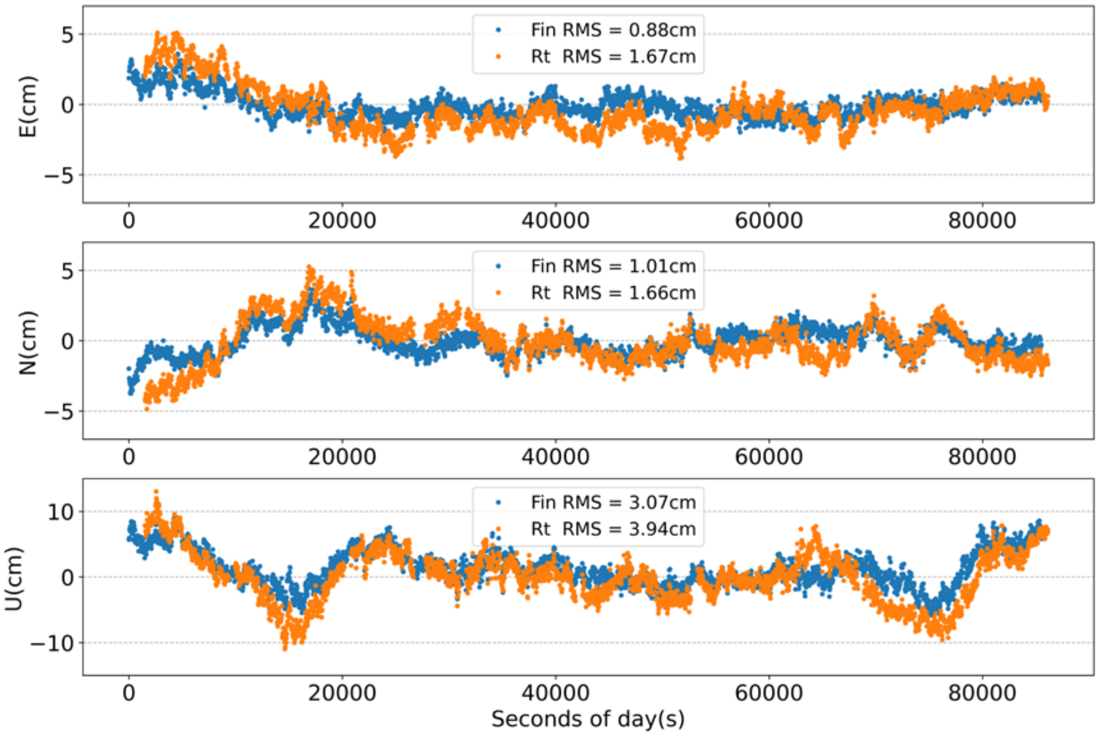

Fig.12 Kinematic PPP results of TWTF station processed by using final products and real-time products on DOY154, 2021

Table 5 Comparison of positioning accuracy of kinematic PPP between using final products and real-time products

Station	RMS of Fin (cm)			RMS of Rt (cm)		
	East	North	Up	East	North	Up
BOAV	1.32	1.32	2.70	2.42	1.77	4.36
CKIS	0.82	0.74	1.57	1.77	1.44	4.79
CMUM	2.71	2.35	7.63	5.97	4.14	10.35
GCGO	0.82	0.70	1.99	2.90	2.06	4.42
IISC	1.43	0.96	3.61	4.52	1.78	5.22
KIRU	0.48	0.46	1.48	2.75	2.56	3.87
KITG	0.67	0.82	1.55	4.45	1.64	5.12
MATG	0.67	0.57	1.39	2.28	1.94	4.75
MKEA	0.86	0.67	1.91	4.05	1.52	3.39
PNGM	0.59	0.74	1.29	7.16	2.83	7.81
QAQ1	0.52	0.43	0.89	2.60	2.38	3.80
RIGA	0.53	0.59	1.23	2.64	3.06	5.50
SGPO	1.10	1.01	2.01	2.57	1.45	3.84
TOW2	0.40	0.63	1.34	2.50	1.21	5.32
TWTF	0.88	1.01	3.07	1.67	1.66	3.94
UCLU	0.89	1.59	4.68	2.28	2.47	5.25
ULAB	0.73	0.68	1.18	2.42	1.81	4.73
UNSA	0.86	0.62	1.94	2.08	1.80	5.06
YKRO	0.82	1.01	2.14	2.35	2.09	4.03
ZAMB	0.51	0.64	1.02	2.82	1.13	3.21
Average	0.88	0.89	2.23	3.11	2.04	4.94

5 Conclusions

IGS RTS provides real-time multi-GNSS satellite orbit and clock correction streams with reference to broadcast ephemeris, which allows us to obtain precise satellite orbit and clock products with the minimum latency and the highest precision. These products can be used in scenarios such as RTPPP where GNSS data needs to be processed quickly.

In this paper, the method of using SSR correction information and broadcast ephemeris to recover precise satellite orbits and clocks is introduced in detail. Then, the SSRC00WHU0 mountpoint of Wuhan University which provides GPS, GLONASS, Galileo, BDS correction information is selected, and the precise satellite orbit and clock products of 7 days are recovered. Taking the final MGEX products released by Wuhan University Analysis Center as a reference, the quality of the real-time precise satellite orbit and clock products is evaluated. Finally, using the real-time products and the final products, the multi-GNSS observation data (GPS, GLONASS, Galileo and BDS) of 20 randomly distributed IGS stations around the world are processed in static and kinematic PPP modes, and the GPS observation data collected by aviation are processed in pseudo real-time kinematic PPP mode, in order to evaluate the application performance of real-time products and the positioning accuracy in RTPPP.

The results of quality analysis show that (1) For the real-time orbit products, the GPS satellites can achieve the accuracy of about 5 cm. Galileo is a little worse, and its accuracy is about 8 cm. The accuracy of GLONASS is similar to that of BDS IGSO/MEO, and it can reach about 15 cm. The accuracy of BDS GEO satellites is low to the level of more than ten meters, which is the worst of all satellites; (2) For the real-time clock products, similarly, GPS satellites have the highest clock accuracy, which can reach 0.43 ns. Galileo satellites are basically at the same accuracy level as GPS satellites, with an average accuracy of 0.44 ns. GLONASS satellites are slightly worse, but they can still achieve sub-nanosecond accuracy of 0.91 ns. The real-time clock accuracy of BDS satellites is the worst at only 3.14 ns. Generally speaking, the real-time orbit and clock products of GPS and Galileo satellites have relatively higher accuracy, followed by GLONASS satellites. The accuracy of BDS satellite is relatively poor, so we should pay attention to it when using it.

For the PPP performance, the experimental results show that (1) Although the positioning accuracy of static PPP, is slightly worse than that using the final products, the average positioning accuracy of 1.57 cm, 0.76 cm and 1.67 cm in east, north and up directions can be achieved by using real-time products. In general, the positioning accuracy in the north direction is the best, followed by the east direction and up directions; (2) For pseudo real-time kinematic GPS PPP, the positioning results obtained by using the final products and the real-time products are very consistent, and the RMS of the position difference in the directions of east, north and up are 8.1 cm, 2.1 cm, 17.9 cm and 8.5 cm, 2.4 cm, 16.5 cm, respectively, compared with the reference results; (3) For GPS, GLONASS, Galileo and BDS kinematic PPP, the average positioning accuracy in east, north and up directions is 3.11 cm, 2.04 cm and 4.94 cm, respectively.

The study basically shows the advantages of the solution of using SSR correction stream to recover the precise satellite orbit and clock products in real time, that is, low latency and high precision, which can play an important role in the application of real-time precise positioning.

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