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Real-Time Precise Point Positioning during Outages of the PPP-B2b Service

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Abstract: The precise point positioning service on B2b signal (PPP-B2b) is a real-time decimeter-level positioning service provided by the BeiDou-3 Global Navigation Satellite System (BDS-3). The service provides users with high-precision orbit and clock corrections through geostationary orbit (GEO) satellites, which means that the PPP-B2b service would be unusable if GEO satellites were blocked. In this study, the performance of PPP-B2b corrections and real-time positioning results during outages of the PPP-B2b service are comprehensively investigated. The results showed that PPP can achieve satisfactory accuracy during outages of the PPP-B2b service by extending the nominal validity of the received PPP-B2b corrections. After extending the PPP-B2b corrections for 10 min, for BDS-3 medium earth orbit (MEO) satellites, the mean root-mean-square error (RMSE) values of the extended orbit were 0.16 m, 0.26 m, and 0.23 m in the radial, along-, and cross-track directions, respectively. The accuracy of the BDS-3 inclined geostationary orbit (IGSO) satellites was slightly worse than that of the BDS-3 MEO satellites; for Global Positioning System (GPS) satellites, the mean RMSE values of the extended orbit were 0.11 m, 0.45 m, and 0.33 m in the radial, along-, and cross-track directions, respectively. In terms of the extended clock, the mean standard deviation (STD) reached 0.17 ns, 0.20 ns, and 0.22 ns after 10 min for the BDS-3 MEO, BDS-3 IGSO, and GPS satellites, respectively. The positioning performance maintained with the extended corrections during the PPP-B2b service outage was evaluated based on five stations in and around China. Our experiments showed that, as long as the interruption time does not exceed 10 min, the real-time positioning with extended PPP-B2b corrections can achieve a comparable accuracy with that obtained following PPP-B2b correction.

Keywords: BDS-3 PPP-B2b service; corrections extension; outage; positioning

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1. Introduction

Precise point positioning (PPP) using global navigation satellite systems (GNSSs) has become a popular technique for various applications, including positioning and atmospheric monitoring, because of its high precision, proficiency, stability, and flexibility. Because the accuracy of PPP largely depends on the accuracy and availability of satellite orbit and clock products, various efforts have been made to produce high-precision satellite orbit and clock products for PPP applications. In recent years, the Multi-GNSS Experiment (MGEX), initiated by the International GNSS Service (IGS), has provided precise orbit and clock products for GNSS users [1,2]. To overcome the latency problem of IGS precision products and meet real-time PPP application requirements, the IGS launched the Real-time Pilot Project (RTPP) in 2007 to provide real-time service (RTS) [3–5]. With access to the RTS, users can receive the orbit and clock corrections to the broadcast ephemeris in the form of a state space representation (SSR) based on the Radio Technical Commission for

Maritime Services (RTCM) and the networked transport of the RTCM via the internet protocol (NTRIP). To date, more than ten institutions, including the GeoForschungsZentrum (GFZ), Center National d'Etudes Spatiales (CNES), and Wuhan University (WHU), have been providing SSR products, promoting the application of real-time PPP in many fields, such as high-precision positioning and atmospheric remote sensing. However, because the IGS real-time precision orbit and clock correction products are broadcast using the internet, poor internet performance or its unavailability will lead to the loss of SSR corrections, resulting in an interruption or at least harmed PPP calculation, which limits its use in areas without stable internet access [6].

In recent years, the GNSSs has undergone significant advancements. The Next Generation Control Segment (OCX) for GPS will be responsible for controlling all modern and legacy GPS satellites, managing all civil and military navigation signals, and providing improved cybersecurity and resilience for GPS operations [7]. Galileo's High-Accuracy Service (HAS) will offer PPP with an accuracy of 20–40 cm globally with 5 min convergence. In addition, regional broadcasts in Europe will be corrected and targeted to converge within 100 s [8]. GLONASS plans to add an IGSO regional component and improve its global geo-distribution control network, currently only covering Russia [9]. China completed the construction of the BDS-3 and began providing positioning, navigation, and timing services to global users in 2020. BDS-3 is composed of three GEO satellites, three IGSO satellites, and twenty-four MEO satellites [10,11]. A prominent feature of BDS-3 is its real-time decimeter-level PPP service via B2b signal (PPP-B2b) based on high-precision satellite orbit and clock corrections, broadcast in real time by the GEO satellites [12,13]. As Yang et al. [14] pointed out, the three-dimensional orbit accuracy of the overlapping arc is about 60 cm when only using regional station observation to determine the satellite orbit; due to the BDS-3 satellite being equipped with inter-satellite links (ISL). Through ISL measurements, the orbit accuracy is about 30 cm and 24-h orbit prediction accuracy also improved from 140 cm to 51 cm; through laser observation evaluation, the radial accuracy can reach 10 cm. In addition, compared with the IGS RTS broadcast via the internet, the orbit and clock corrections in PPP-B2b messages are broadcast on the B2b signal through GEO satellites, which are not restricted by internet conditions.

The three BDS-3 GEO satellites operate in orbits with an altitude of 35,786 km and latitudes of 80°E, 110.5°E, and 140°E. Figure 1 shows the Earth coverage areas of the three GEO satellites, which indicates that they cover most of Asia, Oceania, Europe, and Africa. Although internet conditions do not limit the transportation of PPP-B2b messages, at least one of the three GEO satellites must be viewable to receive the corrections. For users in the Northern Hemisphere, the GEO satellites are always located south of the user, and they may be blocked when buildings are in the line of sight between users and the GEO satellites, which is called the "south wall effect". Similarly, users in the Southern Hemisphere will experience the "north wall effect" [14]. When users are in an "urban canyon" environment where buildings are concentrated, GEO satellite signals are easily blocked by buildings, leading to a loss of B2b signals.

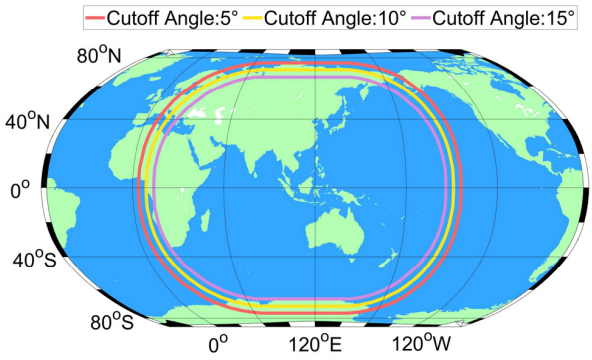

Figure 1. The Earth coverage areas of the three GEO satellites for 5°, 10°, and 15° elevation cut-off angles.

This study attempts to analyze the quality degradation of the PPP-B2b correction over time and its impact on positioning results during outages of the PPP-B2b service. In Section 2, the process of PPP-B2b precision product recovery, the evaluation of PPP-B2b product accuracy, and the repair of missing PPP-B2b precision ephemeris data are briefly described. Section 3 analyzes the continuity of the PPP-B2b corrections, and the quality of the extended corrections. The real-time positioning accuracy maintained using the extended corrections during PPP-B2b signal interruptions is also evaluated. Finally, there is a discussion and conclusion.

2. Methodologies

With the received information transmitted via GEO satellites, the user can recover the PPP-B2b precision products in conjunction with the broadcast ephemeris according to the method provided in the official BeiDou documentation [11]. With the final orbit and clock products from geodetic benchmark (GBM) as the reference, the performances of the PPP-B2b corrections are evaluated in the following subsections.

2.1. The Evaluation Principles of PPP-B2b Precision Products

Because there are some inconsistencies between the PPP-B2b products and the GBM final products, these inconsistencies need to be corrected using the following methods before a comparison can be made.

The satellite positions calculated with the PPP-B2b corrections use the antenna phase center (APC) as the reference point, while the GBM orbit uses the center of mass (CoM) as its reference point [15,16]. The difference between the reference points in these two types of orbit products needs to be eliminated.

The BDS-3 satellite's clock offsets in the B2b products are in reference to the B3I signal, which differ from the GBM final clock offsets estimated based on the ionosphere-free linear combination (IFLC) of the B1I/B3I measurements. This difference can be corrected using the differential code bias (DCB) parameters in the B2b product. In addition, the B2b clock products and the GBM final clock products use different APC correction values [14,17]. The difference between these two types of clock products needs to be eliminated. A double-difference (DD) approach is usually applied for satellite performance evaluation to eliminate the time scale difference between different clock products. In addition, the PPP-B2b products are estimated based on a regional ground observation network. This will lead to a variation in the number of satellites and cause discontinuities in the calculated DD clock offset time series [18].

2.2. The Repair Methods of Matching Error

The B2b signal uses the Issue of Data (IOD) to ensure the relevance of the information content in different message types. The B2b corrections can be used only when the IOD of Navigation (IODN) of the B2b signal broadcast matches the IOD broadcast by the GNSS for the same satellite. The IOD Corr in message type 2 (orbit correction) and satellite message type 4 (clock correction) are used to match the clock and orbit corrections. However, a mismatch between the IODN and the IOD and between the IOD Corr of the orbit corrections and the IOD Corr of the clock corrections can occur at some epochs.

Because the IOD broadcast via the broadcast ephemeris and the IODN in the PPP-B2b message do not update simultaneously, there can be a mismatch between the IOD and the IODN. The amount of missing data due to this mismatch is approximately 1% daily. In this case, the user should continue to apply the old broadcast ephemeris until the IODN in the B2b signal is updated [11].

In the PPP-B2b information, the corrections and corresponding IOD Corr are broadcasted in sequence, and thus there are some occasions when they cannot be matched based on the IOD Corr because the clock correction is updated while the orbit correction is not. In this case, it is recommended to extend the validity of the clock corrections from 12 s to 26 s to use the last matched clock and orbit correction pair until the IOD Corr of the orbit

correction is updated. The amount of missing data due to this mismatch is approximately 0.9% daily.

3. Experiments and Results

3.1. Continuity of B2b Corrections

3.1.1. Jumps in Orbit Corrections

Figure 2 presents the time series of the orbit corrections on DOY 192 in 2022. For the BDS-3 satellites, the correction values in the radial, along-, and cross-track directions were in the ranges of 0.05 m, 0.1 m, and 0.1 m, respectively; for the GPS satellites, the correction values in the radial, along-, and cross-track directions were in the ranges of 0.5 m, 2.0 m, and 1.0 m, respectively, which are much larger than those of BDS-3. This is because the CNAV1 broadcast ephemeris used to calculate the BDS-3 satellite orbit has a higher accuracy than the LNAV broadcast ephemeris used to calculate the GPS satellite orbit [19]. As shown in Figure 2, the orbit corrections of both BDS-3 and the GPS satellites contained frequent jumps. For the BDS-3 MEO satellites, the mean magnitudes of the jumps were 0.017 m, 0.033 m, and 0.029 m in the radial, along-, and cross-track directions, respectively; for the BDS-3 IGSO satellites, the mean magnitudes of the jumps were 0.018 m, 0.039 m, and 0.033 m in the radial, along-, and cross-track directions, respectively; for the GPS satellites, the mean magnitudes of the jumps were 0.039 m, 0.189 m, and 0.081 m in the radial, along-, and cross-track directions, respectively. Due to the existence of these frequent jumps, the orbit corrections were divided into several consecutive arcs. Figure 3 shows the number of orbit arcs with different durations in the studied period. For the BDS-3 satellites, most arcs were over 30 min, while for the GPS satellites, most were within 20 min. It should be noted that the BDS-3 IGSO satellite orbit corrections were more frequent piecewise variations than the BDS-3 MEO satellite orbit corrections, and their continuity was worse.

The jump phenomenon of the orbit corrections during DOY 192–198 in 2022 was further investigated. For the BDS-3 MEO satellites, the mean values of the jumps in the radial, along-, and cross-track directions during this period were 0.018 m, 0.047 m, and 0.042 m, respectively; for the BDS-3 IGSO satellites, the mean values of the jumps in the radial, along-, and cross-track directions during this period were 0.019 m, 0.058 m, and 0.055 m, respectively, which are slightly worse than those of the BDS-3 MEO satellites. For the orbit corrections of the GPS satellites, the mean values of jumps in the radial, along-, and cross-track directions during this period were 0.042 m, 0.211 m, and 0.089 m, respectively, which are larger than those in the BDS-3 satellite orbit corrections. In addition, the average number of consecutive periods for the orbit corrections during this period was also studied. The orbit corrections of the BDS-3 MEO satellites usually contained approximately 11 jumps daily, and approximately 41% of the consecutive periods had a duration of shorter than 30 min; for the BDS-3 IGSO satellites, the orbit corrections usually contained approximately 26 jumps daily, and approximately 62% of the consecutive periods had a duration of shorter than 30 min. The orbit corrections of the GPS satellites contained approximately 17 jumps daily, and approximately 60% of these arcs lasted for less than 30 min. These results show that jumps in BDS-3 IGSO satellite orbit corrections were the most frequent, followed by GPS satellite orbit corrections. In contrast, the jumps in the BDS-3 satellite orbit correction were less frequent, but they also affect its continuity. It is the presence of these frequent jumps that makes the orbit prediction very difficult and unreliable.

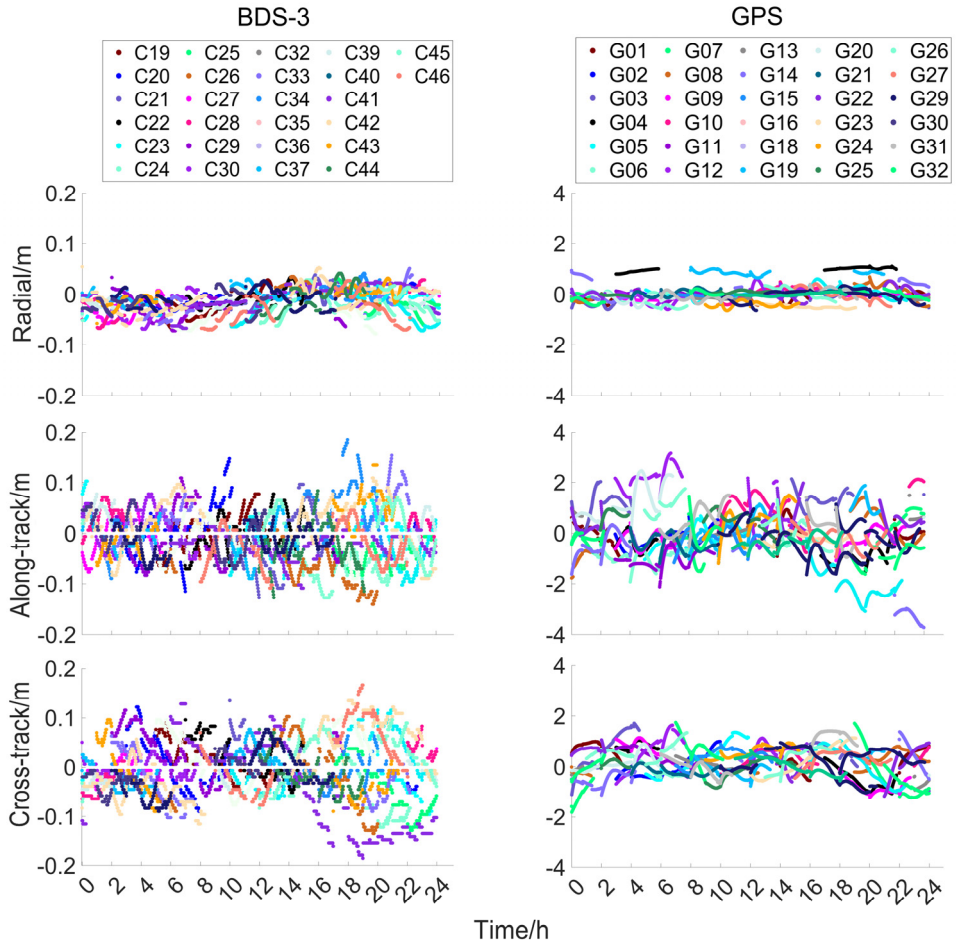

Figure 2. Time series of the orbit corrections of the BDS-3 and the GPS satellites in the radial, along-, and cross-track directions on DOY 192 in 2022.

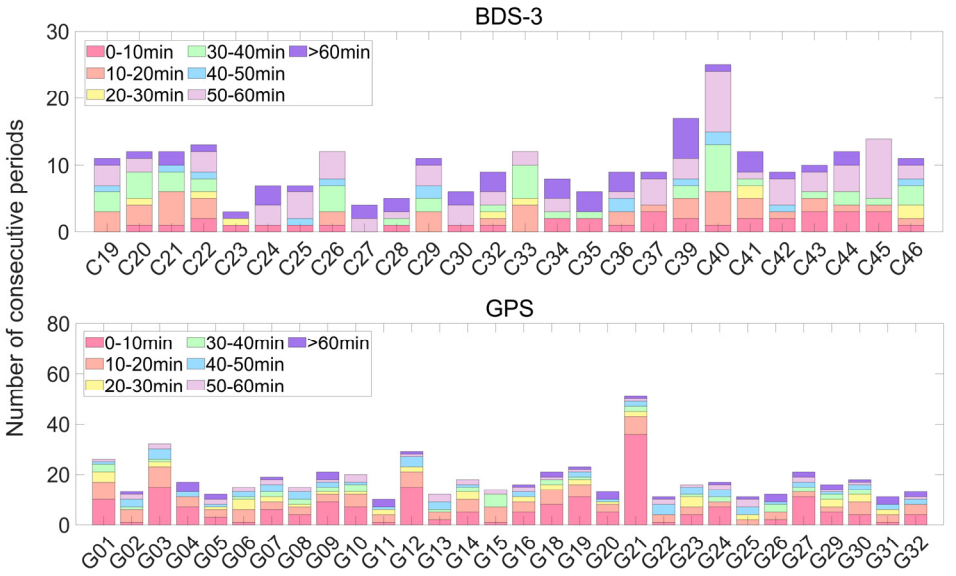

Figure 3. Number of consecutive periods for orbit arcs of the BDS-3 and the GPS satellites with different lengths of time on DOY 192 in 2022. Different colors represent different continuous time periods.

3.1.2. Jumps in Clock Corrections

Figure 4 presents the time series of the clock corrections on DOY 192 in 2022. For most BDS-3 satellites, the values of the clock corrections were in the range of -5 to 5 ns, and only one satellite had a value of approximately -9 ns; for the GPS satellites, the values of the clock corrections were in the range of -1 to 15 ns. As shown in Figure 4, the clock corrections of both the BDS-3 and the GPS satellites contained frequent jumps due to changes in the reference satellite used to calculate the clock offsets. For the BDS-3 and GPS satellites, the mean magnitudes of the jumps were 0.72 ns and 1.43 ns, respectively. Due to the existence of these frequent jumps, the clock corrections were divided into several consecutive arcs. Figure 5 shows the number of clock arcs with different lengths of time in the studied period. For the BDS-3 satellites, most arcs were over 50 min, while for the GPS satellites, most were within 10 min. This phenomenon was also shown in the paper by Ren et al. [19]. Since the clock corrections are estimated based on a regional ground observation network, we speculate that this phenomenon occurs because the GPS reference satellites change more frequently compared to the BDS-3 satellites.

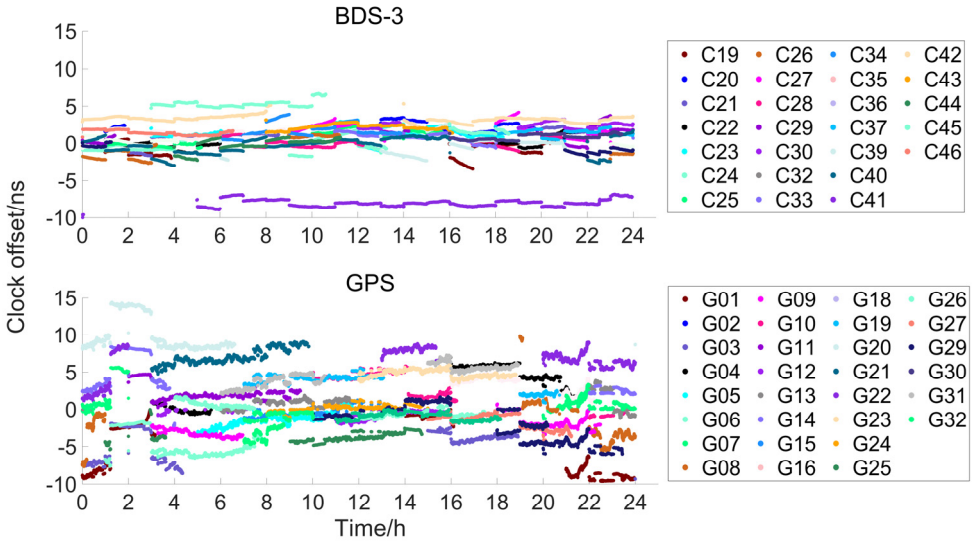

Figure 4. Time series of the clock corrections of the BDS-3 and the GPS satellites on DOY 192 in 2022.

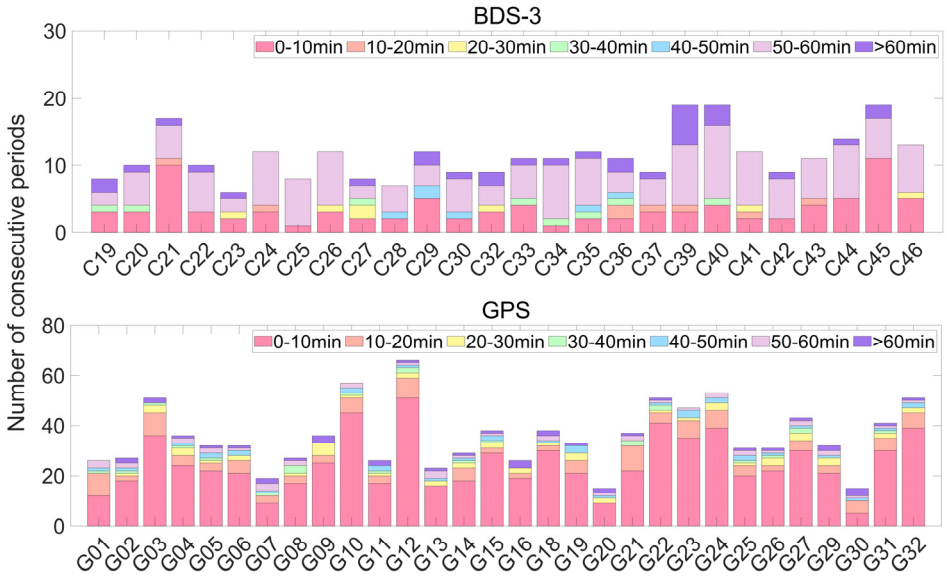

Figure 5. Number of consecutive periods for clock arcs of the BDS-3 and the GPS satellites with different lengths of time on DOY 192 in 2022. Different colors represent different continuous time periods.

It should be noted that since the common jumps in the clock corrections do not affect the coordinate solution, we fixed the common jumps in Figure 6, which become much smoother than those shown in Figure 4. Although some jumps still occur on some individual satellites, and these jumps will have an impact on the positioning solution, many studies have shown that even if these jumps are included, the clock corrections are sufficient to support decimeter-level positioning accuracy standards [18–21].

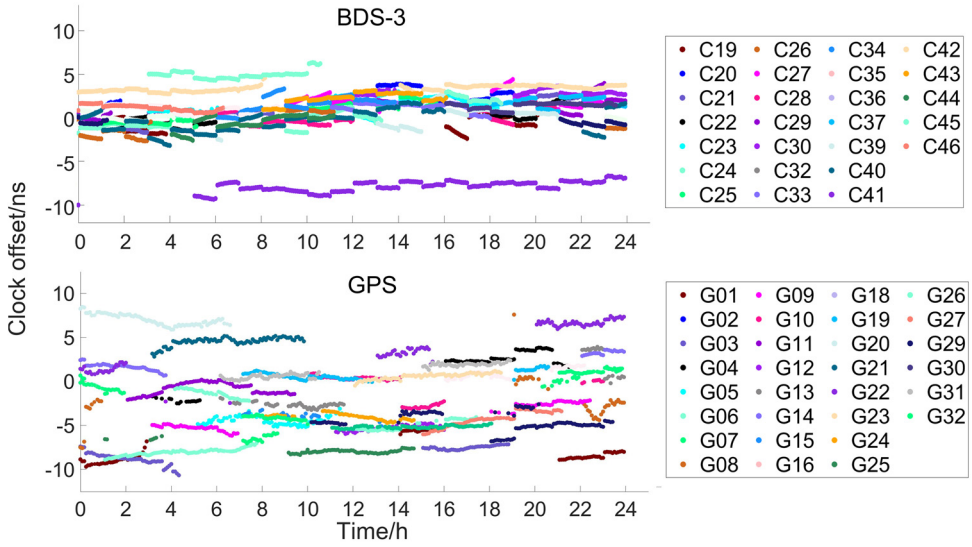

Figure 6. Re-edit of the time series of the clock corrections of the BDS-3 and the GPS satellites on DOY 192 in 2022.

However, both common jumps and jumps present in individual satellites lead to discontinuities in the clock corrections, reducing the lengths of continuous arcs that can be used for predicting, and making it extremely difficult to predict the clock corrections accurately. The jumping phenomenon of clock corrections during DOY 192–198 in 2022 was further investigated. For the BDS-3 satellites, the mean value of the jumps was 0.84 ns; for the GPS satellites, the mean value of the jumps was 1.05 ns. In addition, the clock corrections of the BDS-3 satellites usually contained approximately 11 jumps daily. In comparison, the GPS satellite clock corrections contained approximately 33 jumps daily, and approximately 65% of these arcs lasted for less than 10 min. These frequent jumps in the clock corrections make their prediction very difficult and unreliable.

3.2. The Quality of the PPP-B2b Corrections Degradation over Time

3.2.1. Accuracy of the PPP-B2b Corrections

In this study, the GBM final products provided by the GFZ during DOY 168–198 in 2022 were used to evaluate the performance of the PPP-B2b satellite orbit and clock offsets [22]. Figure 7 shows the RMSE of the BDS-3 and GPS satellite orbits recovered with the PPP-B2b signals with respect to GBM products. For the BDS-3 MEO satellites, the mean RMSE values were 0.14 m, 0.22 m, and 0.20 m in the radial, along-, and cross-track directions, respectively; for the BDS-3 IGSO satellites, the mean RMSE values were 0.15 m, 0.28 m, and 0.23 m in the radial, along-, and cross-track directions, respectively; for the GPS satellites, the mean RMSE values were 0.06 m, 0.25 m, and 0.23 m in the radial, along-, and cross-track directions, respectively. Generally, the PPP-B2b orbit had a much better accuracy in the radial direction than in the along- and cross-track directions. In addition, the orbit accuracy of the BDS-3 IGSO satellites was slightly worse than that of the BDS-3 MEO and GPS satellites.

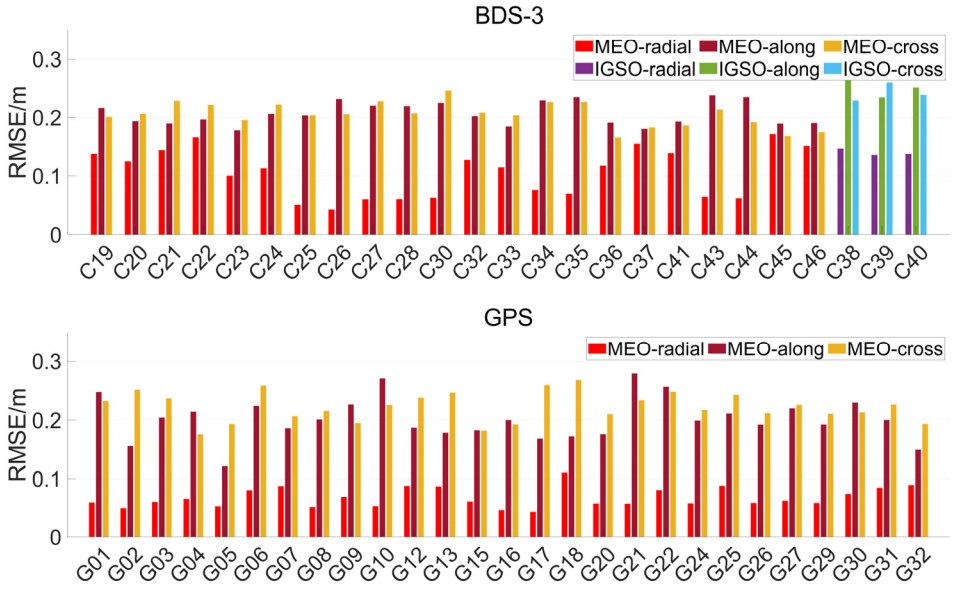

Figure 7. RMSE of the BDS-3 and GPS satellite orbits recovered with the PPP-B2b signals in the radial, along-, and cross-track directions using the GBM orbit products as a reference during DOY 168–198 in 2022.

Figures 8 and 9 show the RMSE and STD of clock offsets of the BDS-3 and GPS satellites. For the BDS-3 MEO satellites, the mean RMSE and STD values were 1.67ns and 0.09 ns; for the BDS-3 IGSO satellites, the mean RMSE and STD values were 1.85 ns and 0.11 ns, which are slightly worse than those of the BDS-3 MEO satellites; for the GPS satellites, the mean RMSE and STD values were 3.67 ns and 0.08 ns. The larger RMSE values associated with the GPS satellite clock corrections may come from the incompleteness of the network distribution used to generate the corrections [18].

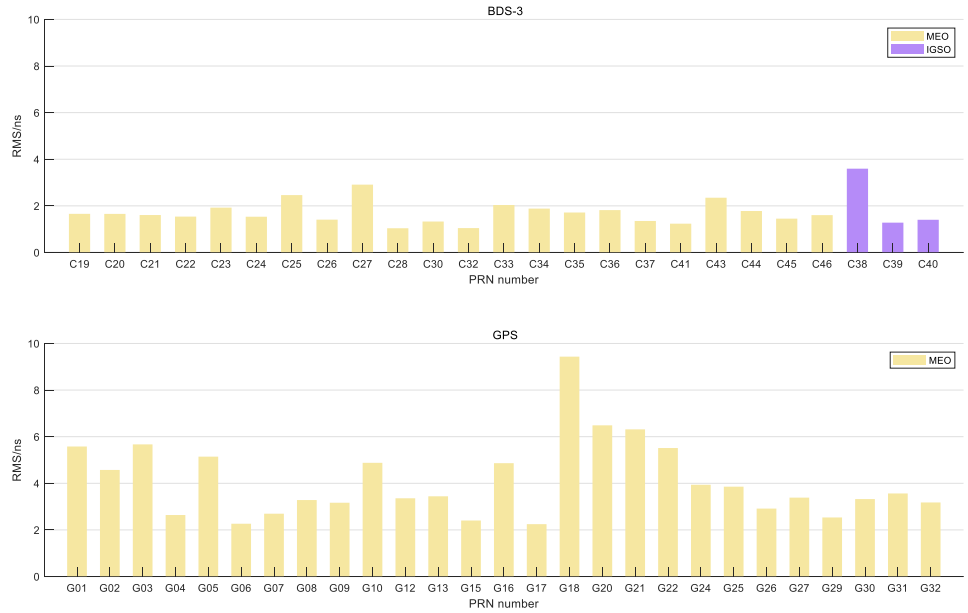

Figure 8. RMSE of the BDS-3 and GPS satellite clock offset recovered with the PPP-B2b signals using the GBM orbit products as a reference during DOY 168–198 in 2022.

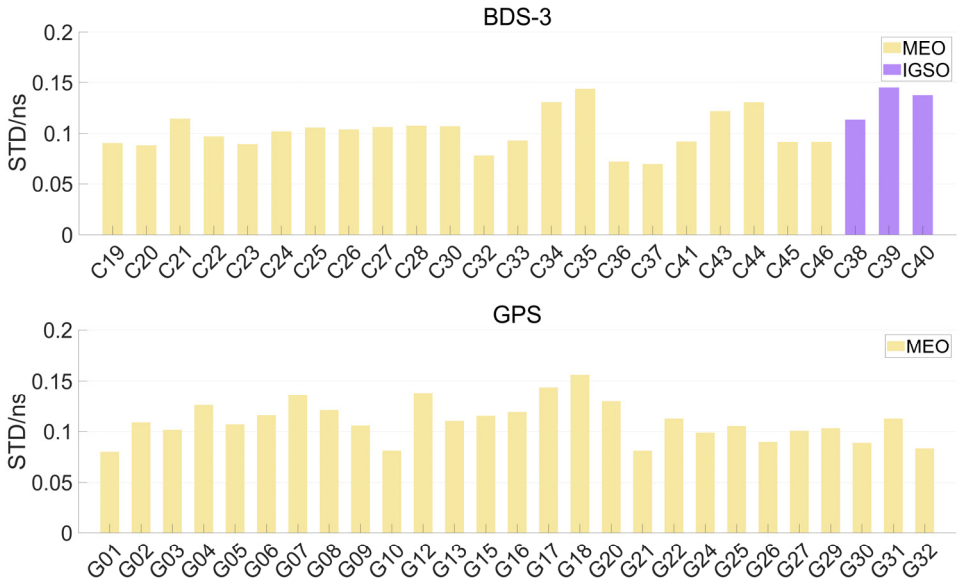

Figure 9. STD of the BDS-3 and GPS satellite clock offset recovered with the PPP-B2b signals using the GBM orbit products as a reference during DOY 168–198 in 2022.

3.2.2. Accuracy of the PPP-B2b Extension Corrections

In this study, the degradation of the PPP-B2b corrections within one hour was investigated using the data on DOY 192 in 2022. In our experiment, we assume that the track to the PPP-B2b signal was lost after we received the pair of clock and orbit corrections at a broadcast epoch on DOY 192. Then, the clock and orbit corrections at this epoch were used as the corrections for the following hour. The differences between these extended corrections and the actual PPP-B2b corrections were then calculated. Then, we moved to the next broadcast epoch and extended the PPP-B2b corrections for the epoch during the following hour, and we calculated the differences between these extended corrections and the actual PPP-B2b corrections. This procedure was repeated from the first epoch to the end epoch, and we thus obtained several time series with a time length of 1 h and an interval of the corrections update. With these results, we then calculated the RMSE of the clock and orbit differences at each epoch for each satellite.

As depicted in Figures 10 and 11, when the last epochs of the orbit and clock corrections were used for the following hour, the RMSE of the extended orbit corrections showed an obvious increase with time. For the BDS-3 satellites, because the accuracy of the broadcast ephemeris is relatively high, the values of the orbit corrections were small (within the range of -10 to 10 cm), and the RMSE of the orbit error in the radial, along-, and cross-track directions was less than 6 cm even after one hour. However, for the GPS satellites, the RMSE of the extended orbit corrections in the radial, along-, and cross-track directions reached approximately 0.4 m, 0.8 m, and 0.8 m, respectively, after one hour. In terms of the clock correction, the RMSE was less than 1 ns and 2 ns for most BDS-3 and GPS satellites, respectively.

To further investigate the quality of the extended orbit and clock corrections, a more comprehensive experiment was conducted with the data during the period of DOY 192–198 in 2022. The accuracy of the extended corrections was evaluated using the GBM products. As shown in Table 1, for the BDS-3 satellites, the accuracy of the extended orbit within 10 min can still be maintained at a similar level to the real-time PPP-B2b orbit, and the accuracy of the extended orbit of BDS-3 IGSO satellites was slightly worse than that of BDS-3 MEO satellites. For GPS satellites, the accuracy of the extended orbit deteriorated more rapidly than that of BDS-3, especially in the along- and cross-track directions. The mean RMSE of the GPS satellites reached 0.45 m and 0.8 m in the along-track directions after 10 min and 1 h, respectively. As shown in Tables 2 and 3, the mean RMSE and STD of the extended GPS satellite clock deteriorated much faster than the BDS-3 satellite. The

mean STD values of the BDS-3 MEO, BDS-3 IGSO, and GPS satellites reached 0.17 ns, 0.20 ns, and 0.22 ns after 10 min, respectively.

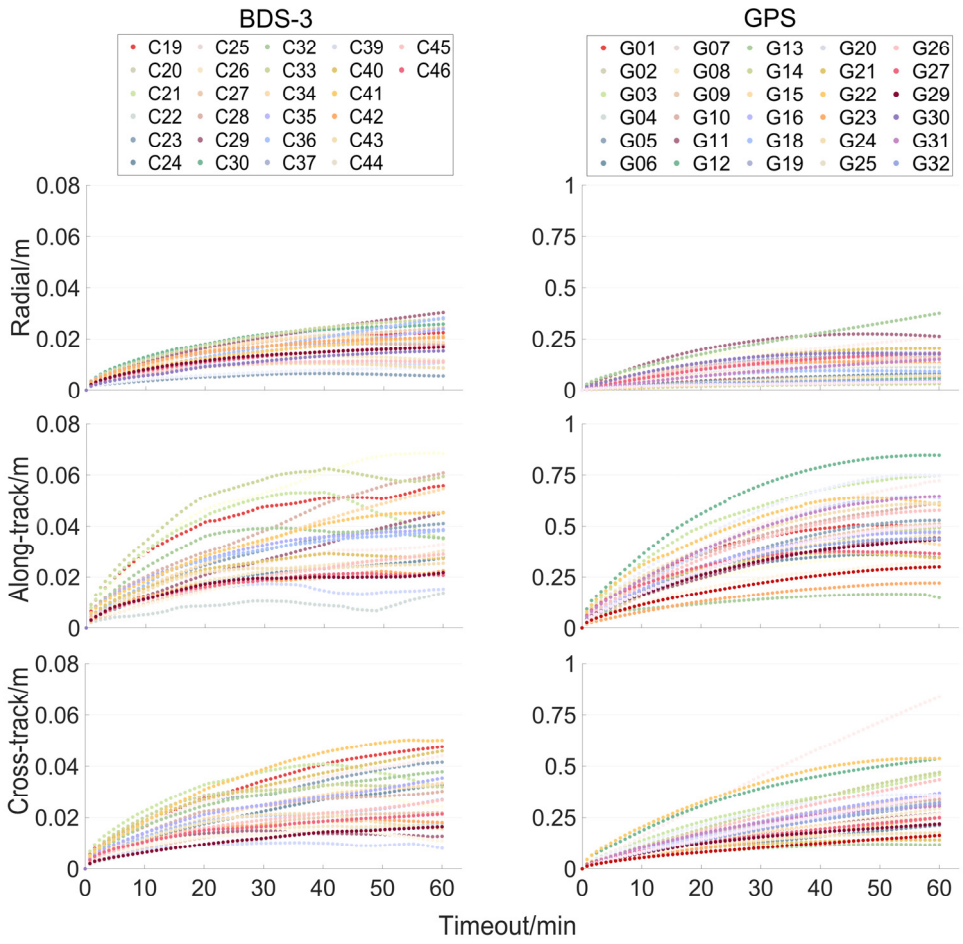

Figure 10. RMSE of the extended orbit corrections of the BDS-3 and GPS satellites in the radial, along-, and cross-track directions on DOY 192 in 2022.

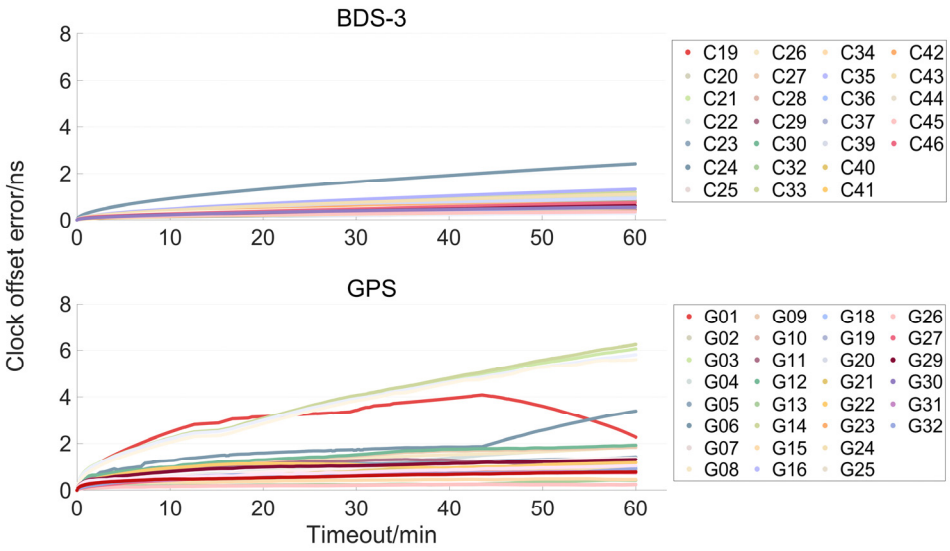

Figure 11. RMSE of the extended clock corrections of the BDS-3 and GPS satellites in the radial, along-, and cross-track directions on DOY 192 in 2022.

Table 1. Mean RMSE of the PPP-B2b orbit products recovered with extension corrections using the GBM orbit products as a reference during DOY 192–198 in 2022.

Extension Time/s	BDS-3 MEO			BDS-3 IGSO			GPS		
	R/m	A/m	C/m	R/m	A/m	C/m	R/m	A/m	C/m
30	0.14	0.23	0.20	0.14	0.29	0.24	0.07	0.29	0.25
60	0.14	0.23	0.21	0.15	0.29	0.24	0.07	0.32	0.26
120	0.15	0.24	0.21	0.15	0.30	0.25	0.08	0.34	0.27
180	0.15	0.24	0.21	0.15	0.30	0.25	0.08	0.35	0.28
300	0.15	0.25	0.22	0.15	0.30	0.26	0.09	0.38	0.29
600	0.16	0.26	0.23	0.16	0.31	0.27	0.11	0.45	0.33
1200	0.17	0.29	0.25	0.18	0.34	0.29	0.13	0.58	0.40
1800	0.18	0.31	0.27	0.19	0.35	0.31	0.18	0.67	0.45
3600	0.20	0.36	0.30	0.22	0.38	0.35	0.23	0.80	0.58

Table 2. Mean RMSE of the PPP-B2b clock products recovered with extension corrections using the GBM clock products as a reference during DOY 192–198 in 2022.

Extension Time/s	BDS-3 MEO	BDS-3 IGSO	GPS
	Clock/ns	Clock/ns	Clock/ns
30	1.75	1.88	3.89
60	1.79	1.94	3.96
120	1.83	2.01	4.05
180	1.86	2.07	4.10
300	1.91	2.14	4.19
600	2.01	2.27	4.35
1200	2.16	2.44	4.57
1800	2.27	2.57	4.76
3600	2.52	2.85	5.16

Table 3. Mean STD of the PPP-B2b clock products recovered with extension corrections using the GBM clock products as a reference during DOY 192–198 in 2022.

Extension Time/s	BDS-3 MEO	BDS-3 IGSO	GPS
	Clock/ns	Clock/ns	Clock/ns
0–30	0.11	0.12	0.13
0–60	0.12	0.13	0.16
0–120	0.13	0.14	0.17
0–180	0.13	0.15	0.17
0–300	0.14	0.17	0.19
0–600	0.17	0.20	0.22
0–1200	0.20	0.24	0.28
0–1800	0.23	0.27	0.31
0–3600	0.29	0.33	0.41

3.3. Positioning Quality Degradation over Time

3.3.1. Accuracy of the Real-Time PPP-B2b Positioning

A simulated kinematic experiment was conducted with PPP-B2b corrections and real-time observations at five stations. The specific processing strategies adopted in the PPP and locations of the stations are listed in Tables 4 and 5, respectively.

Table 4. Processing strategies for the simulated kinematic PPP-B2b experiment.

Item	Processing Strategy
System	BDS-3 + GPS
Frequencies	GPS L1/L2 and BDS-3 B1I/B3I
Observation data	Real-time data stream
Satellite orbit and clock	B2b corrections + Broadcast ephemeris
Ionospheric delay	Ionosphere-free linear combination with dual frequency
Tropospheric delay	Estimation zenith total delay and horizontal gradient parameters
Antenna PCO/PCV	Igs14.atx
Elevation cut-off angle	7°

Table 5. Locations of the five stations selected in the simulated kinematic PPP-B2b experiment.

Site	Latitude (°)	Longitude (°)	Height (km)
BJ01	40.07	116.27	0.09
JFNG	30.52	114.49	0.07
HKSC	22.32	114.14	0.02
KSKT	39.50	75.93	1.27
MSSA	36.14	138.35	1.63

Figure 12 shows the mean RMSE of the real-time PPP-B2b positioning errors for the five stations during DOY 355–361 in 2022. The errors in the north and east directions for the five stations were less than those in the up direction. The three-dimensional (3D) errors of the positioning results for stations located in China, i.e., BJ01, JFNG, and HKSC, were in the range of 0.11–0.14 m, while those for stations located in the northwest and outside of China, i.e., KSKT and MSSA, were in the range of 0.27–0.34 m. These results show that the real-time positioning accuracy varies from region to region, and the positioning accuracy is better in areas near the center of China. This is because different regions have different numbers of observable satellites that can be used for PPP-B2b corrections, and different observation geometries. The number of available satellites with PPP-B2b correction and the observation geometries of these satellites in China are better than those in the surrounding areas [20].

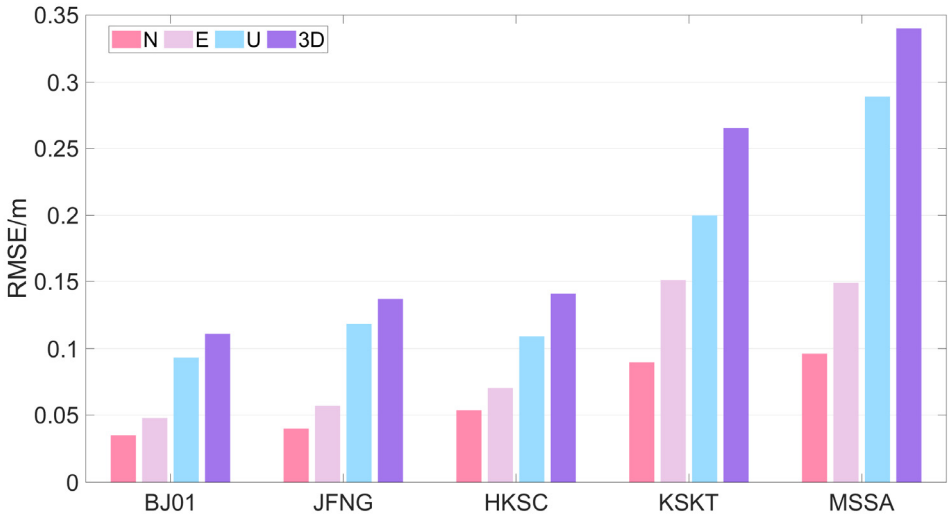

Figure 12. Mean RMSE of the real-time PPP-B2b positioning errors of the simulated kinematic PPP-B2b solutions for the five stations in the north, east, and up directions, and 3D coordinates, during DOY 355–361 in 2022.

3.3.2. Accuracy of the Real-Time PPP-B2b Positioning Using Extended Corrections

To investigate the real-time positioning performance of using extended corrections during PPP-B2b signal interruptions, the PPP-B2b signal was artificially interrupted at GPST 16:30 on DOY 297 in 2022. In this simulation experiment, the interruption time length was increased from 10 min to 60 min with a step of 10 min. As shown in Figure 13, the positioning accuracy during an interruption of 10 min remained comparable to that without the interruption. For an interruption of 20 min, the 3D positioning error reached 20 cm, and quickly decreased to 12 cm when reacquiring the PPP-B2b signal. As the interruption time increased from 10 min to 60 min, the 3D positioning error gradually increased from 12 cm to 57 cm. The increase in positioning error was especially obvious in the up direction, with the maximum RMSE of approximately 0.5 m after 53 min, which greatly affected the three-dimensional positioning accuracy. Although the 3D positioning error increased significantly as the interruption continued, it quickly returned to a satisfactory level (20 cm) after reacquiring the PPP-B2b corrections. In general, the shorter the interruption time is, the better the positioning accuracy will remain during the interruption period.

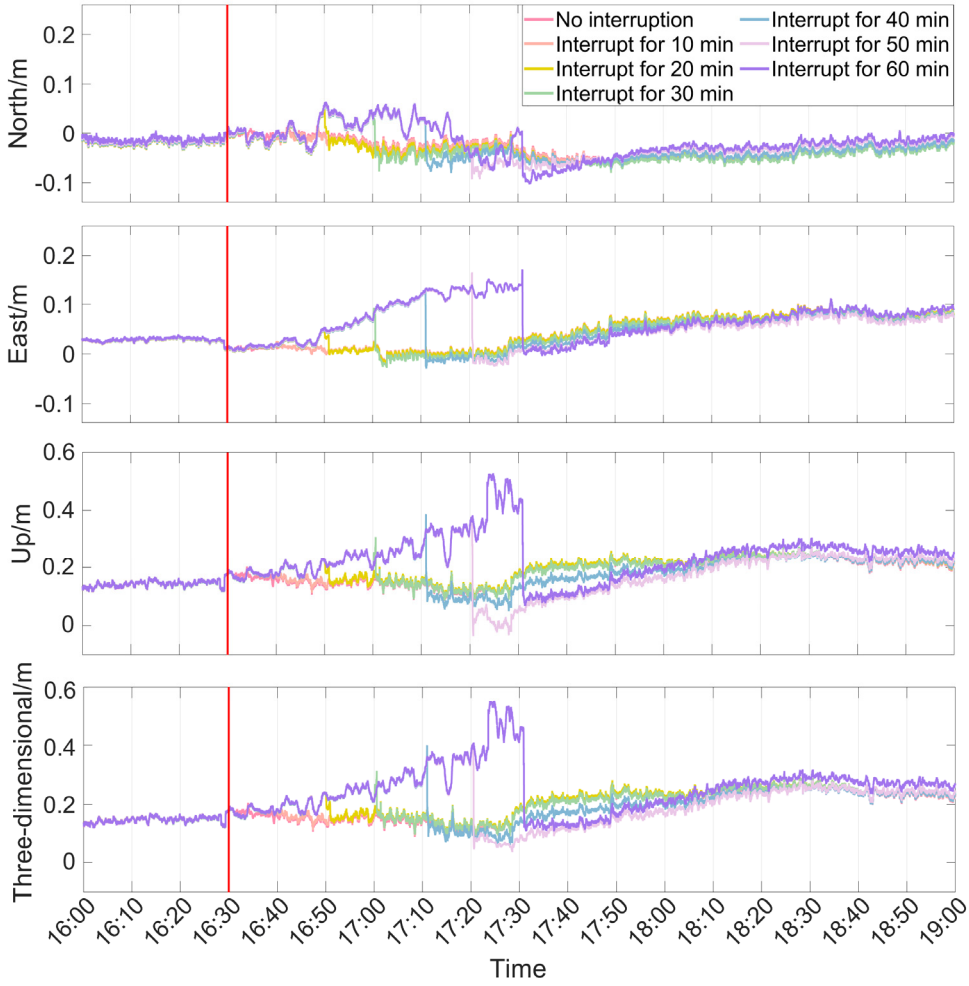

Figure 13. Effects of different interruption lengths on the simulated kinematic PPP-B2b positioning results for the BJ01 station in the north, east, up, and 3D directions on DOY 279 in 2022.

This interruption experiment was also conducted at the other four stations. As shown in Figure 14, a longer interruption will generally lead to a larger positioning error when the extended corrections during the interruption of the PPP-B2b signal are used. In most cases, the position accuracy obtained with extended corrections during the first 10 min of the interruption period will be similar to that derived with received PPP-B2b corrections. With an increase in the interruption period, the positioning error with extended corrections

will increase steadily and become much larger than that determined with received PPP-B2b corrections. The results also indicate that the positioning errors show very obvious dependence on location.

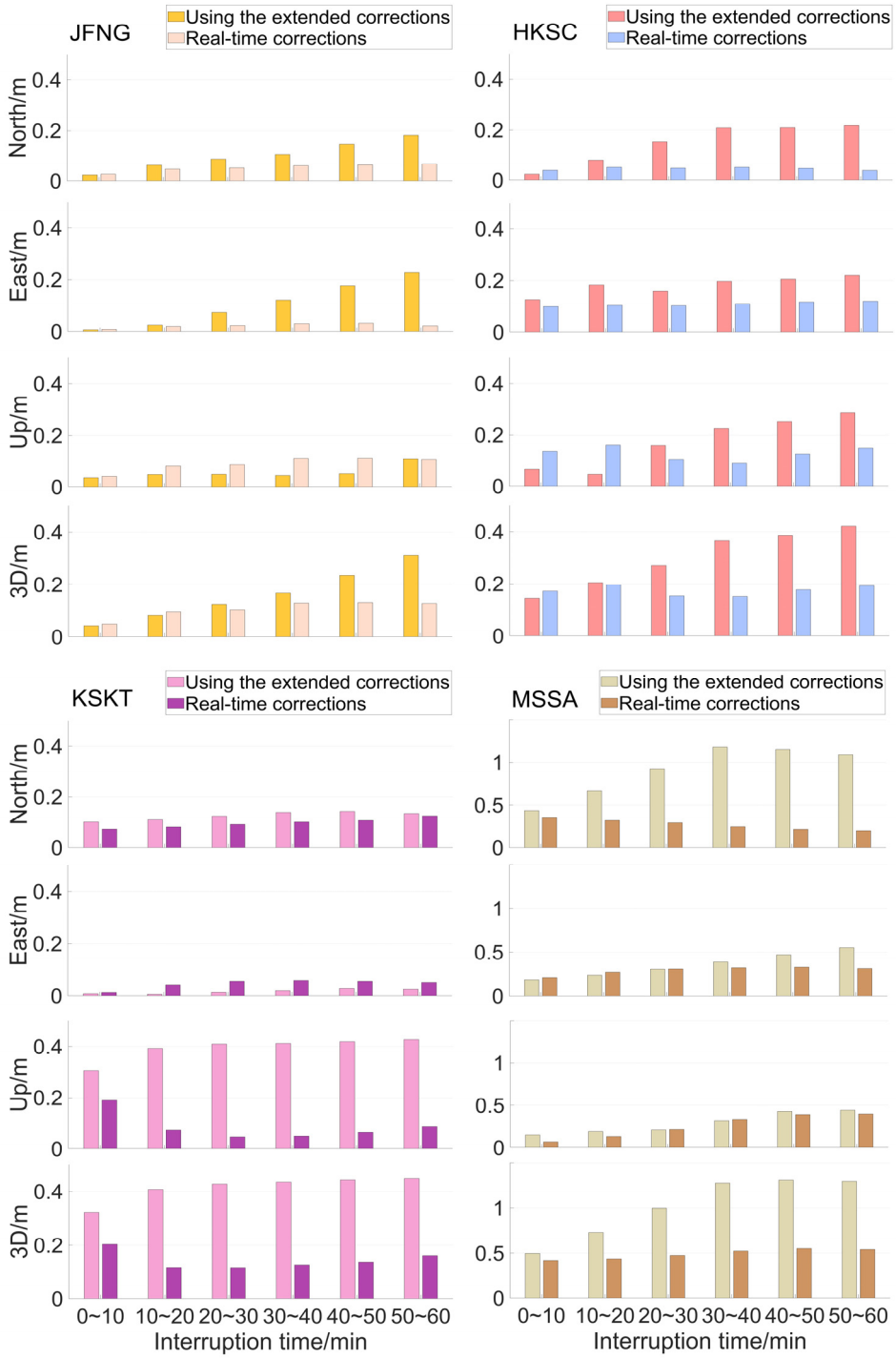

Figure 14. Accuracy of the remaining four stations in the north, east, and up directions, and 3D coordinates after the interruption at 16:30:00 and without the interruption.

To give a more general statistical result regarding the PPP performance with different interruption periods, we artificially interrupted the PPP-B2b signal at GPST 6:30, 11:30, 16:30, and 21:30 during DOY 355–361 in 2022, and counted the mean RMSE of the 3D positioning error during the interruptions. As Table 6 shows, for stations located in China, i.e., BJ01, JFNG, and HKSC, during interruption of the PPP-B2b signal, the RMSE of the

positioning results increased slowly from below 15 cm in the first 10 min to larger than 30 cm during the 50–60 min of interruption. For the two stations located in Xinjiang, China (KSKT) and Japan (MSSA), the RMSE of the positioning results increased from approximately 30 cm in the first 10 min of the interruption period to 60 cm during 50–60 min of interruption. In general, during the first 10 min of the interruption period, the accuracy of the positioning results obtained with extended corrections was almost identical to that obtained with true PPP-B2b corrections.

Table 6. Mean RMSE of 3D positioning error of the simulated kinematic PPP-B2b solutions at different times for the five stations during DOY 355–361 in 2022.

Interruption Times/min	3D Error/m				
	BJ01	**JFNG**	**HKSC**	**KSKT**	**MSSA**
No Interruption	0.111	0.137	0.141	0.266	0.340
0–10	0.118	0.138	0.142	0.289	0.351
10–20	0.143	0.159	0.167	0.354	0.434
20–30	0.179	0.233	0.210	0.432	0.479
30–40	0.218	0.319	0.262	0.461	0.513
40–50	0.262	0.405	0.328	0.505	0.566
50–60	0.305	0.413	0.369	0.558	0.689

In addition to the above simulated kinematic experiments, a real-time kinematic experiment was conducted to further investigate the PPP performance with extended PPP-B2b corrections during outages of the PPP-B2b service. This experiment was conducted on DOY 361, 2022 with a GNSS receiver mounted on a slow-moving platform. As shown in Figure 15, the receiver started operation at GPST 6:15, and the 3D positioning accuracy took 65 min to converge to 8 cm. During the movement of the platform, we artificially interrupted the tracking of the GEO satellites at 7:30 and restored the tracking at 7:40. During the period when the PPP-B2b was not available (7:30–7:40), the 3D RMSE of the positioning results obtained with extended PPP-B2b corrections was 0.10 m, which is very close to the values achieved before and after the interruption, i.e., 0.07 m and 0.09 m, respectively. This real-time kinematic experiment proves that it is reasonable to continue the PPP process by extending the validity of PPP-B2b to 10 min when the PPP-B2b is not available.

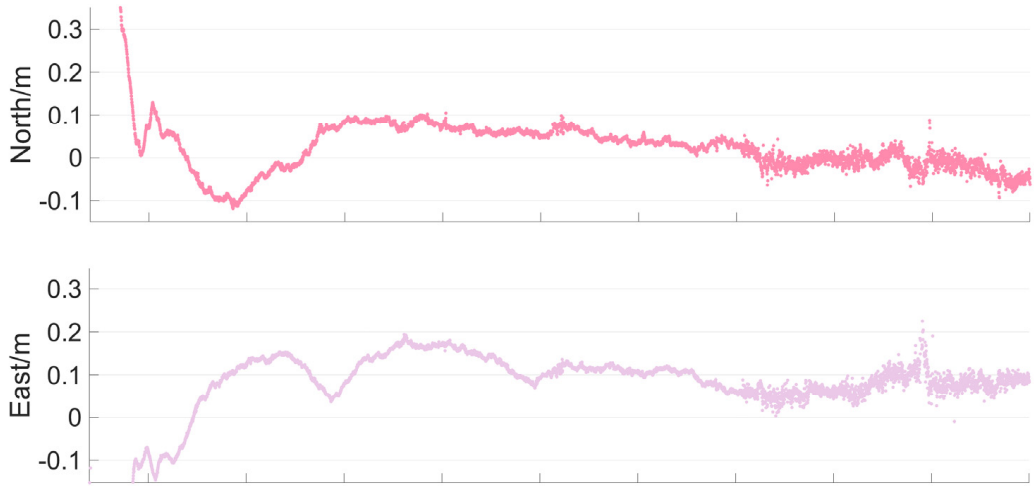

Figure 15. *Cont.*

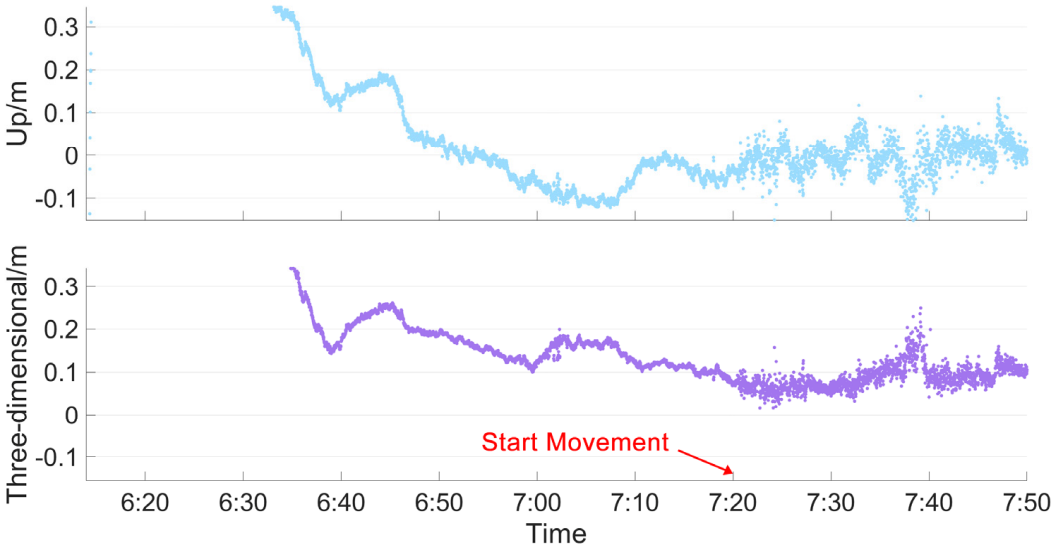

Figure 15. Real-time PPP-B2b positioning accuracy in kinematic mode, including PPP-B2b service interruptions.

4. Discussion

The introduction of the PPP-B2b service offers a new possibility for real-time positioning. To achieve real-time precise positioning, it is necessary to have access to continuously available, reliable, and accurate orbits and clocks products [23]. The PPP-B2b service requires that GEO satellites be visible, but in urban environments, these satellites may be blocked by the "south wall effect" or "north wall effect" for short periods, preventing users from receiving continuous precise orbits and clocks, which significantly impacts real-time positioning results. Therefore, it is important to consider strategies for maintaining real-time positioning during short interruptions of the PPP-B2b service when using this service.

In this study, the characteristics of the PPP-B2b corrections during DOY 192–198 in 2022 were analyzed. The results demonstrate that the PPP-B2b corrections were subject to frequent jumps due to broadcast ephemeris updates and other factors. Specifically, the orbit corrections for the BDS-3 MEO, BDS-3 IGSO, and GPS satellites jumped on average 11, 26, and 17 times per day, respectively. Similarly, the clock corrections jumped on average 11 and 33 times per day for BDS-3 and GPS satellites, respectively. These jumps can make the data set used for predicting discontinuous, and can significantly affect the predictability of the PPP-B2b corrections. Several studies have demonstrated that combining corrections with broadcast ephemerides can improve continuity, which is also beneficial for predicting continuous periods [19–21]. However, systematic jumps and errors still occur for the PPP-B2b precision ephemerides. When a break occurs at the next ephemeris moment in which a jump occurs, it can still result in a lack of continuous data sets for predicting. To address this issue, we decided to use the last updated set of corrections before the outage occurred to compensate for the missing corrections. The accuracy of the extended corrections during DOY 192–198 in 2022 was evaluated using the GBM product as a reference to validate the effectiveness of this method. As shown in Tables 1–3, the accuracy of the extended corrections gradually decreased with increasing extension time, with similar accuracy for BDS-3 MEO and BDS-3 IGSO satellites, and GPS satellites showed a greater level of deterioration in accuracy compared to BDS-3 satellites. The mean RMSE of the extended orbit for BDS-3 satellites exceeded 30 cm with a 1 h extension, while the mean RMSE of the extended orbit for GPS satellites reached as high as 80 cm; the mean STD values of the extended clock for BDS-3 and GPS satellites were approximately 0.3 and 0.4 ns, respectively. However, when the extension time did not exceed 10 min, the mean RMSE of the BDS-3 satellite extended orbit was below 30 cm, and the mean RMSE of the GPS satellite extended orbit increased by 4 cm, 16 cm, and 8 cm in the radial, along-, and cross-track directions,

respectively; in terms of the extended clock, the mean STD values of the BDS-3 MEO, BDS-3 IGSO, and GPS satellites reached 0.17 ns, 0.20 ns, and 0.22 ns after 10 min, respectively. Overall, the accuracy of the extended corrections remained within an acceptable range, indicating that the quality of the PPP-B2b corrections will not be significantly degraded in the short term and will maintain good accuracy.

To further investigate the impact of extended corrections on PPP, the positioning accuracy of the simulated kinematic model using extended corrections was evaluated at five stations in and around China. As shown in Table 6, the results showed that there was a significant decrease in positioning accuracy at all stations as the interruption time increased, with the degree of this decrease being dependent on the region. At stations with high-quality PPP-B2b positioning services, such as BJ01, JFNG, and HKSC, the decline in accuracy was gradual, with positioning accuracy dropping by approximately 10 cm when the interruption time reached 20–30 min. In contrast, at stations with lower-quality PPP-B2b positioning services, such as KSKT and MSSA, the decline was more severe, with positioning accuracy dropping by approximately 10 cm when the interruption time reached 10–20 min. In this experiment, the interruption time was kept below 10 min, which allowed all stations to maintain their real-time positioning accuracy. Additional kinematic experiments were conducted to assess the performance of the extended correction during the PPP-B2b service interruptions. As shown in Figure 15, while positioning accuracy decreased as the interruption time increased, the RMSE of 3D positioning accuracy during the interruption was 0.1 m—slightly worse than the 0.07 m and 0.09 m achieved before and after the interruption. These experiments demonstrate that the use of extended corrections during PPP-B2b service outages can compensate for interruptions within 10 min.

5. Conclusions

In this study, the PPP-B2b correction error characteristics and PPP-B2b service interruption real-time precise point positioning were comprehensively investigated. The findings indicate that there were frequent jumps in the PPP-B2b corrections, and these jumps led to a lack of sufficiently long continuous data arcs for correction predictions. For this reason, it becomes almost impossible to make a reliable prediction of the PPP-B2b corrections. An alternative method is to continue using the PPP-B2b information received at the last epoch before losing track of the PPP-B2b signal. However, the performance of this method depends highly on the degradation of the PPP-B2b corrections with time. The results demonstrated that the quality of extended corrections remains satisfactory in the short term, and when the extension time is 10 min, the impact on the accuracy of the BDS-3 satellite orbit and clock is at the centimeter level, the impact on the accuracy of the GPS satellite orbit in the along-track direction is at the decimeter level, and the impacts on the remaining orbit directions and clock are at the centimeter level. Additionally, the results revealed that the performance of the extended corrections varies depending on the variations in positioning accuracy across different regions. In areas with high-quality PPP-B2b positioning services, i.e., BJ01, JFNG, and HKSC, the RMSE of real-time positioning results was approximately 13 cm, the available time for extended correction was also longer, and the RMSE was approximately 20 cm with outages of 20–30 min. Nevertheless, even in regions with suboptimal PPP-B2b positioning services, such as KSKT and MSSA, the use of extended corrections can preserve the accuracy level of real-time positioning within 10 min. Therefore, it is advisable to use extended corrections for positioning within a time frame of 10 min or less.

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