Research Article

Modelling and Assessment of BDS-3 Real-time Precise Point Positioning Time Transfer Based on PPP-B2b Service

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In 2020, users in and around China had access to a new real-time precise point positioning (RTPPP) service with the BeiDou global navigation satellite system (BDS-3) B2b (PPP-B2b) signal. In this study, the quality of PPP-B2b products is first assessed and compared with the CNAV1 broadcast ephemeris. Then a mode of BDS-3 PPP time transfer with PPP-B2b (B2b-RTPPP) is developed and evaluated in static and kinematic modes. The results demonstrate that the discontinuity of orbit is improved by applying the PPP-B2b, and its root mean square errors (RMSEs) are 0.081 m, 0.165 m, and 0.107 m in the radial, along-track, and cross-track components, respectively. The standard deviation (STD) of the PPP-B2b clock offset is 0.08 ns, greatly better than that of the broadcast clock offset. For time transfer, the type A uncertainty of the B2b-RTPPP solution is approximately 0.1 ns in static mode, and approximately 0.3 ns in kinematic mode. The B1I/B3I B2b-RTPPP time transfer solution performs better than the B1C/B2a solution. For frequency stability, the modified Allan deviation (MDEV) of the B2b-RTPPP solution is comparable to that of the post-processing solution. The B1C/B2a combination has better short-term frequency stability than B1I/B3I, while the long-term frequency stability of B1C/B2a is worse. In addition, the contribution of the differential code bias (DCB) to B2b-RTPPP time transfer is also investigated. The type A uncertainty of the B2b-RTPPP solution without DCB correction is worse than that of the B2b-RTPPP solution with DCB correction. The B1C/B2a B2b-RTPPP solution without DCB correction has better frequency stability than the B1I/B3I B2b-RTPPP solution.

1. Introduction

With the development of the global navigation satellite system (GNSS), GNSS time transfer is widely used in the fields of time scale maintenance, scientific studies, and dense map optimization [1–4] with its advantages of global, all-day, being able to operate continuously, high precision, and flexibility. In the future, it may also be combined with location-based service (LBS) for private needs [5, 6], which can provide support for heterogeneous networks, indoor navigation, and in-vehicle Internet [7–9]. In the early stages, GNSS time transfer was conducted with broadcast ephemeris and pseudorange observations, while its accuracy was relatively poor, which is 10-20 ns due to the large errors in broadcast ephemeris and pseudorange observations [10].

Since Zumberge et al. first proposed the precise point positioning (PPP) technique, many researchers have shown a great deal of interest in it due to its capacity to provide centimeter- to decimeter-level positioning services [11, 12]. The PPP technique uses undifferenced pesudorange and carrier phase observations for time transfer [13]. Because of its higher measurement accuracy and lower noise of carrier phase observations, PPP has higher accuracy and better short-term stability than pseudorange-only solutions, which brings promising opportunities for time transfer. PPP was formally applied for coordinated universal time and temps atomique international (TAI) computation by the (BIPM), and the type A uncertainty of GPS PPP solution was 0.3 ns [14, 15]. An approach of PPP time transfer with phasemeter measurements was proposed by Defraigne et al. [16], and the stability of the time link is improved by the solution. In
addition, a clock model is used by Ge et al. [17] to investigate the PPP time transfer performance using multi-GNSS observations, and they concluded that the multi-GNSS solution performs better than the single-system solution. However, PPP is mainly applied in post-processing scenarios because of the long latency of the international GNSS service (IGS) final products. Shorter latency and high accuracy of products are actually needed for real-time cases like ionospheric delay inversion and precise timing. For this background, RTPPPP has been studied by many research institutions and scholars. The IGS launched the real-time pilot project in 2007 and provided real-time service (RTS) in 2013 [18]. GPS and GLONASS users could use the IGS RTS to get the receiver’s position and clock offset in time. Li et al. [19] analyzed the time transfer performance using the online streaming of IGS RTS. However, the IGS RTS depends on the Internet, which may be interrupted due to equipment failure and network outage. Therefore, satellite-based augmentation services were transmitted to avoid the interruptions caused by network outages, which has a wider range of service, including marine areas. Nowadays, the Quasi-Zenith Satellite System can broadcast the centimeter-level augmentation services for Japanese users via the L6 signal [20], while the Galileo High Accuracy Service (HAS) can transmit corrections for GPS and Galileo users [21]. However, neither of them supports the BeiDou global navigation satellite system (BDS-3).

To make it easier to implement the BDS-3 RTPPP autonomously, BDS-3 was fully completed in 2020. BDS-3 consists of 3 geostationary earth orbit (GEO), 24 medium earth orbit (MEO), and 3 inclined geosynchronous orbit (IGSO) satellites. BDS-3 adds B1C, B2a, and B2b signals while retaining the B1I and B3I signals of BDS-2, which can provide RTPPPP service to users in and around China via the BDS-3 PPP (PPP-B2b) signal [22, 23]. Currently, the PPP-B2b signal is broadcast by the GEO satellites and transmits differential correction messages of the I-component for BDS-3 and GPS. The broadcast ephemeris, including satellite mask, orbit correction parameters, user range accuracy index (URAI), differential code bias (DCB) correction and clock correction parameters, with their message types of 1, 2, 2, 3 and 4, respectively [26]. The Issue of Data (IOD) is used to perform reliable matching between PPP-B2b products and broadcast ephemeris, which includes IOD of state space representation (IOD SSR), IOD of pseudo-random noise mask (IODP), and IOD of navigation (IODN), in addition to the IOD of orbit and clock corrections (IOD Corr). The SSR’s issue number, which must be constant between all message types, is represented by the IOD SSR. The satellite mask’s data issue number, which is contained in message types 1 and 4, is denoted by the IODP. The user can use it to verify the match between the satellite mask and clock corrections. The IODN contained in message type 2 is used to match the broadcast ephemerides. Message types 2 and 4 both contain the IOD Corr. For the shared satellites, Only if the clock’s IOD Corr and the orbit’s IOD Corr are the same can the PPP-B2b products be used.

2. Methods

2.1. B2b-RTPPP model. Currently, the PPP-B2b signal contains only the first four message types, which can provide correction messages for BDS-3 CNAV1 and GPS LNAV broadcast ephemeris, including satellite mask, orbit correction parameters, user range accuracy index (URAI), differential code bias (DCB) correction and clock correction parameters, with their message types of 1, 2, 2, 3 and 4, respectively [26]. The Issue of Data (IOD) is used to perform reliable matching between PPP-B2b products and broadcast ephemeris, which includes IOD of state space representation (IOD SSR), IOD of pseudo-random noise mask (IODP), and IOD of navigation (IODN), in addition to the IOD of orbit and clock corrections (IOD Corr). The SSR’s issue number, which must be constant between all message types, is represented by the IOD SSR. The satellite mask’s data issue number, which is contained in message types 1 and 4, is denoted by the IODP. The user can use it to verify the match between the satellite mask and clock corrections. The IODN contained in message type 2 is used to match the broadcast ephemerides. Message types 2 and 4 both contain the IOD Corr. For the shared satellites, Only if the clock’s IOD Corr and the orbit’s IOD Corr are the same can the PPP-B2b products be used.

2.1.1. Recovery of the Precise Orbits. PPP-B2b provides the satellite orbit corrections in radial (R), along-track (A), and cross-track (C) components. Since the broadcast ephemeris provides the satellite orbit position under the ECEF framework, PPP-B2b satellite orbit corrections must be converted into the corrections in the ECEF, which can be expressed as follows [26].

\[
\delta X = [\mathbf{e}_r, \mathbf{e}_a, \mathbf{e}_c] \cdot \delta \mathbf{O},
\]

where \(\delta \mathbf{O} = [\delta O_r, \delta O_a, \delta O_c]^T\), denoting the PPP-B2b orbit vector; and \([\mathbf{e}_r, \mathbf{e}_a, \mathbf{e}_c]^T\) is an orthogonal matrix consisting of three unit vectors, which can be described as follows [26].

\[
\begin{align*}
\mathbf{e}_r &= \frac{\mathbf{r}}{r} \\
\mathbf{e}_c &= \frac{\mathbf{r} \times \mathbf{\dot{r}}}{|\mathbf{r} \times \mathbf{\dot{r}}|} \\
\mathbf{e}_a &= \mathbf{e}_c \times \mathbf{e}_r,
\end{align*}
\]

where \(\mathbf{r}\) and \(\mathbf{\dot{r}}\) denote the satellite position vector and velocity vector, respectively. The precise satellite position can be calculated as follows by combining (1) and (2).
\[ X_{\text{prec}} = X_{\text{brdc}} - \delta X, \]  
(3)

where \( X_{\text{prec}} \) is the recovered precise satellite position; and \( X_{\text{brdc}} \) denotes the satellite position obtained from the broadcast ephemeris.

### 2.1.2. Recovery of Precise Clock Offset

The precise clock offset can be recovered by applying the PPP-B2b clock offset correction as follows.

\[ t_{\text{prec}} = t_{\text{brdc}} - \frac{C_0}{c}, \]  
(4)

where \( t_{\text{prec}} \) is the recovered precise clock offset; \( t_{\text{brdc}} \) is the satellite clock offset obtained from the broadcast ephemeris; \( C_0 \) indicates the PPP-B2b clock offset corrections; and \( c \) is the speed of light in the vacuum.

### 2.1.3. DCB Correction

The different observations contain different hardware delays associated with the signal tracking mode due to the different satellite tracking modes [26]. Therefore, in efforts to realize synchronous processing of signals at various frequencies, the hardware delay must first be avoided. The following is the recovery algorithm.

\[ \overline{P} = P - \text{DCB}, \]  
(5)

where \( P \) is the initial pseudorange observations from the receiver; and \( \overline{P} \) is the corrected pseudorange observations.

### 2.1.4. Evaluation Methods of Precise Orbit and Clock Offset

The precise satellite position recovered by PPP-B2b is referenced to the antenna phase center (APC), whereas the GBM final product provides the satellite position taking the center of mass (CoM) as a benchmark. Therefore, it should unify the satellite position with CoM. In addition, the coordinate datum is the same for both products, both are international terrestrial reference frames. That is

\[ X_{\text{CoM}} = X_{\text{APC}} + A \cdot \delta X_{\text{PCO}}, \]  
(6)

where \( X_{\text{CoM}} \) represents the satellite’s CoM; \( X_{\text{APC}} \) is the satellite’s APC; \( A \) denotes the transformation matrix; and \( \delta X_{\text{PCO}} \) is the satellite phase center offset (PCO) position.

In the terms of the satellite clock offset, the B3I signal is taken as a benchmark for the BDS-3 clock offset, while it refers to the B1I/B3I IF signal for the GBM final products. Therefore, the corresponding DCB must be applied before comparing the two products. The formula can be expressed as [27]:

\[ T_{\text{IF B1B3}} = T_{\text{B2b}} - \frac{f_3^1}{f_1^3 - f_3^2}, \]  
(7)

where \( T_{\text{IF B1B3}} \) represents the clock offset referring to B1I/B3I IF signal; \( T_{\text{B2b}} \) denotes the precise clock offset calculated from PPP-B2b; \( f_1 \) and \( f_3 \) are the frequencies of the B1I and B3I signals, respectively; and \( DCB_{\text{B1B3I}} \) is the DCB between the B1I and B3I signals.

After removing the inconsistency between PPP-B2b and GBM clock offset using PPP-B2b DCB, a dual-difference method is used to eliminate systematic bias between the different time scales maintained by different analysis centers [28].

\[ \forall \Delta dt_{a,b}^i = (dt_{a}^i - dt_{b}^i) - \frac{1}{M} \sum_{i=1}^{M} (dt_{a}^i - dt_{b}^i), \]  
(8)

where \( \forall \Delta \) is the dual-difference operator; \( dt \) is the satellite clock offset; and \( M \) is the satellite number at each epoch. Since the satellite number is not fixed, \( \forall \Delta dt_{a,b}^i \) has a discontinuity during the test period, affecting the clock error’s standard deviation (STD). \( \forall \Delta dt_{a,b}^i \) is calculated according to the literature [29]:

\[ \forall \Delta dt_{a,b}^i = \forall \Delta dt_{a,b}^i - \Delta D_{t-1}, \]

\[
\Delta D_{t-1} = \begin{cases} 
\frac{1}{M} \sum_{i=0}^{M} \forall \Delta dt_{a,b}^i \big|_{(t-1)} & \text{if } \abs{\forall \Delta dt_{a,b}^i} \geq 0.1 \text{ ns}, \\
0 & \text{if } \abs{\forall \Delta dt_{a,b}^i} < 0.1 \text{ ns},
\end{cases}
\]

where \( \Delta D_{t-1} \) can compensate for systematic bias exceeding \( \pm 0.1 \text{ ns} \); and \( \forall \Delta \Delta dt_{a,b}^i \big|_{(t-1)} \) is the difference between the \( \forall \Delta dt_{a,b}^i \big|_{t} \) value at epoch \( t \) and the \( \forall \Delta dt_{a,b}^i \big|_{(t-1)} \) value at epoch \( t-1 \) for satellite \( i \).

### 2.1.5. BDS-3 B2b-RTPPP Model

The dual-frequency (DF) IF combination of pseudorange and carrier phase observations can be expressed as [30, 31]
the frequency amplification factor; \(d_c\) and \(d_e\) stand for the uncalibrated code hardware delays at receiver and satellite ends (m/s), respectively; \(\lambda_{IF}\) denotes the carrier wavelength of IF combination signal; \(b_r\) and \(b_s\) are the uncalibrated carrier phase hardware delay at receiver and satellite ends (cycle); \(N_{IF}\) is the IF combination phase ambiguity (cycle); \(\varepsilon_{IF}\) and \(\zeta_{IF}\) are the observation noise and uncorrected errors of pseudorange and carrier phase IF combination (m), respectively. In this paper, 1, 3, 4, and 5 denote B1I, B3I, B1C, and B2a signals, respectively.

For PPP-B2b, since the B3I signal is used as the frequency reference, the PPP-B2b clock offset absorbs the B3I signal’s pseudorange hardware delay. That is \(c \, dt_{br,d} = c \, dt + c d_{B3I}\). Therefore, for B1I/B3I and B1C/B2a combinations, (11) and (12) can be rewritten as

\[
\begin{align*}
P_{IF13} &= \rho + c (dt_{r,IF13} - dt_{br,d}) - \alpha_{13} DCB_{13}^e + T + \varepsilon_{IF13}, \\
L_{IF13} &= \rho + c (dt_{r,IF13} - dt_{br,d}) + T + \lambda_{IF13} N_{IF13} + \zeta_{IF13}, \\
\end{align*}
\]

(11)

\[
\begin{align*}
P_{IF45} &= \rho + c (dt_{r,IF45} - c \, dt_{br,d}) - \alpha_{45} DCB_{45}^e + c \beta_{45} DCB_{53}^e + T + \varepsilon_{IF45}, \\
L_{IF45} &= \rho + c (dt_{r,IF45} - c \, dt_{br,d}) + T + \lambda_{IF45} N_{IF45} + \zeta_{IF45}, \\
\end{align*}
\]

(12)

with

\[
\begin{align*}
d_{r,IFmn} &= d_t + d_{r,IFmn}, \\
\alpha_{mn} &= \frac{f_m^2}{f_m^2 - f_n^2}, m, n = 1, 3, 4, 5; m \neq n, \\
DCB_{mn}^e &= d_e^m - d_e^n, \\
\beta_{mn} &= -\frac{f_n^2}{f_m^2 - f_n^2}, \\
\lambda_{IFmn} N_{IFmn} &= \alpha_{mm} \lambda_m \left(b_{r,m} - b_{r,n} + N_m\right) + \beta_{mn} \lambda_n \left(b_{r,n} - b_{r,n} + N_n\right) - c \, dt_{r,IFmn} + cd_{B3I},
\end{align*}
\]

(13)

where \(d_{r,IFmn}\) denotes the receiver clock offset of the IF combination; \(\alpha\) and \(\beta\) represent the frequency factors. Hence, the parameter vector to be estimated can be expressed as

\[
X = \left[ X, d_{r,IFmn}, T, N_{IFmn} \right],
\]

(14)

where \(X\) is the vector of position deltas relative to the receiver’s prior position.

2.2. Time Transfer Model. For two GNSS receivers connected with atomic clocks, the receiver clock offset is the difference between the local time (i.e., BeiDou time 1 (BDT1) and BDT2) and the reference time, which can be expressed as

\[
\begin{align*}
dt_1 &= BDT_1 - ref, \\
dt_2 &= BDT_2 - ref,
\end{align*}
\]

(15)

where \(dt\) denotes the receiver clock offset; \(BDT\) is the local time; \(ref\) denotes the reference time. Then, the difference between the two receiver clocks can be expressed as (16), and Figure 1 depicts the principle of B2b-RTPPP time transfer.

\[
\Delta t = dt_1 - dt_2 = BDT_1 - BDT_2.
\]

(16)

3. Experimental Data and Processing Strategies

Using the SINO K803 kit, which can receive binary PPP-B2b corrections and save them into daily files, we collected PPP-B2b messages over two days from March 27 to March 28, 2022, i.e., day of year (DOY) 86-87, 2022, to investigate the BDS- B2b-RTPPP time transfer performance. Then, the quality of PPP-B2b products is assessed and compared with the CNAV1 broadcast ephemeris. Five stations in and around China are selected, each of which has the capability of tracking four BDS-3 signals. In addition, the USUD station is selected as the central node for time transfer, and four time links (SHA1-USUD, TLM2-USUD, GUA1-USUD, and CUSV-USUD) are designed, as displayed in Figure 2. The information of those selected stations is listed in Table 1. This study utilizes the B1I/B3I and B1C/B2a IF combination observations to implement B2b-RTPPP time transfer. Table 2 lists the PPP-B2b data processing strategies.

4. Results

4.1. Evaluation of PPP-B2b Correction Accuracy. In this section, the quality of the PPP-B2b products and the CNAV1 broadcast ephemeris is evaluated. Since there are
more than 120 monitoring stations distributed around the world and the GBM product is calculated using the B1I/B3I IF observations of three-day arc, which have high accuracy of about 2.0 cm for orbit and about 75.0 ps for clock offset, the GBM final product is taken as the reference.

4.1.1. Accuracy of Precise Orbit. The PPP-B2b’s and CNAV1’s orbit errors for March 27, 2022, are depicted in Figure 3. The orbit errors of both the PPP-B2b and CNAV1 are within 0.6 m in the R direction and within 1.0 m in both the A and C directions. Surprisingly, no significant differences are found in the orbit errors of the two. The sequence of the PPP-B2b orbit errors is more continuous than that of the CNAV1, which may be explained by the hourly noncontinuous variation of the CNAV1 broadcast ephemeris orbit errors caused by the hourly update of the CNAV1 broadcast ephemeris, while the discontinuity is greatly corrected after applying the PPP-B2b orbit products. This
suggests that the PPP-B2b real-time orbits appear to be more consistent with the GBM final precise orbits, resulting in faster filter convergence. Note that the C31, C38, C39, and C40 satellites are excluded because the information of C31 is not provided by PPP-B2b, and IGSO satellites have worse orbit and clock offset accuracy than MEO satellites [25].

The root mean square errors (RMSEs) of the orbit errors are analyzed over the test period, as shown in Figure 4, to further assess the quality of the PPP-B2b orbit products, and the average RMSEs of the PPP-B2b and CNAV1 orbits in the RAC directions are summarized in Table 3.

The RMSEs of the PPP-B2b orbits directions are comparable to that of the CNAV1 broadcast ephemeris in the

![Figure 3: Time sequence of orbit errors for PPP-B2b (a) and CNAV1 (b) in the RAC directions (unit: m).](image1)

![Figure 4: RMSEs of the PPP-B2b (left) and CNAV1 (right) (unit: m).](image2)
4.2. Analysis of BDS-3 B2b-RTPPP Time Transfer Performance. Five stations (see Figure 2) are selected to evaluate the BDS-3 B2b-RTPPP time transfer performance. The experiments are carried out with the post-processing PPP solution employing B1I/B3I IF combination observations from the GBM final products in static mode as a reference (the true value).

4.2.1. Analysis of the Continuity for B2b-RTPPP Time Transfer. Figure 7 shows the clock differences between the B2b-RTPPP solutions and post-processing PPP solutions for the USUD and TLM2 stations. There is a gap, called day-boundary, for the GBM when the time is 24. However, this gap does not show for the PPP-B2b, which is because the GBM final clock product adopts a daily data processing strategy, leading to the gap between two days for the GBM clock offset, while the PPP-B2b clock product is calculated by the Kalman filter epoch by epoch [38, 39]. Therefore, the clock difference is continuous for the PPP-B2b. Based on the above analysis, the quality of the PPP-B2b clock product is poorer than that of the GBM clock product, resulting in a larger noise in B2b-RTPPP time transfer [39]. Furthermore, the clock offset obtained by the B2b-RTPPP solution presents volatility. The reason for this may be that the time reference maintained by the GBM final product is more stable than that of the PPP-B2b product.

4.2.2. Analysis of Static B2b-RTPPP Time Transfer Performance. The clock errors of static B2b-RTPPP time transfer solutions on DOY 86-87 are displayed in Figure 8. There are three findings here. First, the static B2b-RTPPP solution has excellent consistency with the post-processing PPP time transfer solutions, with peak-to-peak values of clock error within 1 ns for each time link. Second, the mean values of clock errors between B1I/B3I and B1C/B2a IF PPP solutions exhibit a clear systematic bias due to the different hardware delays absorbed by different IF combinations. Third, the B1I/B3I IF PPP solution has a smoother clock

| Table 3: Average RMSE of the PPP-B2b and CNAV1 (unit: m). |
|-----------------|---|---|---|
|                | Radial | Along-track | Cross-track |
| PPP-B2b        | 0.081  | 0.165       | 0.107       |
| CNAV1          | 0.086  | 0.173       | 0.115       |

4.1.2. Accuracy of Precise Clock Offset. The STD is employed to assess the accuracy of the PPP-B2b clock offsets with the GBM clock product as a benchmark. Since broadcast ephemeris and precise ephemeris clock offset have different frequency references and timescale datum, they must be unified using Equations (7) to (10). In this work, the DCB is adopted to avoid the difference in frequency, and the difference in timescale datum is reduced by the average clock offset (see (8)).

Figure 5 depicts the sequence of the PPP-B2b and CNAV1 clock offset errors. The hourly update of the broadcast ephemeris is also responsible for the hourly discontinuity in the sequence of the CNAV1 clock offset error. Excitingly, the continuity and smoothness of the broadcast ephemeris clock offset are significantly improved by the PPP-B2b clock products, demonstrating a greater accuracy for the PPP-B2b real-time clock offset. However, there is a clear stratification of PPP-B2b clock offset errors, with satellite-specific clock offset errors reaching approximately 5 ns. The systematic bias, which can be absorbed by the phase ambiguity and have no effect on the time transfer, is mainly related to the pseudorange observations [37].

Considering the bias between satellites mentioned above, the STDs of the clock offset errors were calculated during the test period to further assess the precision of the PPP-B2b clock offset, as displayed in Figure 6. The STD of PPP-B2b clock offset errors is smaller than that of CNAV1. Furthermore, the PPP-B2b’s STD is approximately 0.03–0.20 ns, with a mean STD of 0.08 ns, and the CNAV1’s STD is approximately 0.20–0.90 ns, with a mean STD of 0.54 ns.

Figure 5: Time sequence of clock errors for the PPP-B2b (top) and CNAV1 (bottom) clock offsets.

RAC directions. The average RMSEs of the PPP-B2b orbit errors in the RAC directions are approximately 0.081 m, 0.165 m, and 0.107 m, and the average RMSEs of the CNAV1 broadcast ephemeris orbit errors in the RAC directions are 0.086 m, 0.173 m, and 0.115 m, respectively. The results indicate that the accuracies of the PPP-B2b orbits are slightly better than that of CNAV1 broadcast ephemeris orbits. However, the orbit accuracy is not significantly improved by PPP-B2b. In addition, the R direction has the minimum orbit error for both PPP-B2b and CNAV1 broadcast ephemeris, with an RMSE within 0.1 m. However, the accuracy in the A and C directions is relatively poor.

Figure 7: Average RMSE of the PPP-B2b and CNAV1 (unit: m).
error sequence than the B1C/B2a IF PPP solution, indicating that the B1I/B3I IF combination has better time transfer performance. There may be two reasons to explain it. First, the stability of B1I-B3I DCB is better than that of B1Cp-B3I and B2ap-B3I DCB [40], which causes the larger error term in the B1C/B2a IF B2b-RTPPP time transfer [41]. Second, the reason may be that the post-processing solution used as a reference also adopts B1I/B3I IF combination, which has better consistency with the B1I/B3I real-time solution of PPP-B2b. The discontinuity between two consecutive days is caused by the day-boundary of the GBM clock products according to the conclusions in Section 4.2.1.

To further investigate the static B2b-RTPPP time transfer performance, the STD and average STD values of the clock errors are calculated to indicate the type A uncertainty of time transfer, as listed in Table 4. The B1I/B3I solution has smaller STD values than B1C/B2a solution for each time link, suggesting that the B1I/B3I IF combination has a better time transfer performance, which supports our previous conclusions. In addition, the STDs of B1I/B3I and B1C/B2a solutions are all within 0.1 ns, and the average STD values of B1I/B3I and B1C/B2a solutions are 0.070 ns and 0.087 ns, respectively. Compared to the B1C/B2a, the improvement of B1I/B3I ranges from 5.38% to 46.43%.

Frequency stability is another indicator of time transfer performance. The modified Allan deviation (MDEV) is employed to evaluate the frequency stability of time links. Since the TLM2 and USUD stations are linked to high-performance on-board clocks, we focus on evaluating the frequency stability of the TLM2-USUD time link.

Now let us turn to Figure 9, depicting the MDEV of B1I/B3I and B1C/B2a IF combinations PPP for the TLM2-USUD time link. The frequency stability of static B2b-RTPPP solutions shows roughly agreement with that of the post-processing PPP solution. In detail, the short-term frequency stability of the post-processing PPP solution is similar to that of the B2b-RTPPP solution, while it performs worse in the long term due to the day-boundary of the GBM final clock product. In addition, the MDEV of the B1C/B2a IF B2b-RTPPP solutions (8.9 × 10^-14 at 120 s) performs better in the short term than that of the B1I/B3I IF combination (1.0 × 10^-13 at 120 s), while it (2.9 × 10^-15 at 30720 s) is worse than that of the B1I/B3I IF combination (2.0 × 10^-15 at 30720 s) in the long term. There may be two explanations for this: (1) The noise amplification factor of the B1I/B3I IF combination (3.5275) is larger than that of the B1C/B2a IF combination (2.5883) [42], which means that the short-term frequency stability of the B1I/B3I PPP solution is worse. After filtering convergence, however, it has little effect on long-term frequency stability. (2) The error terms, such as DCB, antenna PCO, and satellite clock offset, are not fully corrected, which makes a significant contribution to the long-term frequency stability of the B1C/B2a IF combination. Because PPP-B2b provides the DCB, antenna PCO, and satellite clock offset, the B3I signal as a frequency reference, the incomplete correction of the above error terms has a greater effect on the long-term frequency stability when using the B1C/B2a IF combination for time transfer. The results indicate that the accuracy of the PPP-B2b DCB product needs to be improved in the near future.

### 4.2.3. Analysis of Kinematic B2b-RTPPP time transfer Performance

In Figure 10, each panel presents the clock errors between kinematic B2b-RTPPP solutions and the post-processing solutions for each time link. Compared to
the static B2b-RTPPP solution, the sequence of clock error for the kinematic solution is smoother, while it has greater fluctuation, with the peak-to-peak values of clock error approximately 2 ns for each time link. This may be related to the greater noise variance of kinematic PPP than that of static PPP in data processing. Figure 10 also shows a clear systematic bias between B1I/B3I and B1C/B2a solutions. Note that the day-boundary does not exist in kinematic PPP solutions due to the greater noise variance of kinematic PPP.

Table 5 represents the STD and average STD values of the clock error. The mean STD values of the B1I/B3I and B1C/B2a PPP solutions are 0.305 ns and 0.329 ns, respectively. The improvement of B1I/B3I ranges from 4.065% to 11.728% compared with B1C/B2a. The B1I/B3I IF combination also has smaller STD values than B1C/B2a IF combination, indicating that B1I/B3I B2b-RTPPP time transfer performance is better than B1C/B2a B2b-RTPPP time transfer performance, which further supports our previous findings.

Now turn to Figure 11, which depicts the MDEV of the kinematic B2b-RTPPP solutions for the TLM2-USUD time link. The frequency stability of the B1I/B3I solution is comparable to that of the B1C/B2a solution. In the short term, the MDEV of the B1C/B2a IF combination ($4.6 \times 10^{-13}$ at 120 s) also outperforms the B1I/B3I IF combination.

**Table 4: STDs for each time link (unit: ns).** The improvement indicates the static B2b-RTPPP time transfer performance using B1I/B3I combination compared with that of using the B1C/B2a combination in STD values.

| Time link   | B1I/B3I | B1C/B2a | Improvement (%) |
|-------------|---------|---------|-----------------|
| SHA1-USUD   | 0.045   | 0.084   | 46.43           |
| TLM2-USUD   | 0.067   | 0.080   | 16.25           |
| GUA1-USUD   | 0.080   | 0.091   | 12.09           |
| CUSV-USUD   | 0.088   | 0.093   | 5.38            |
| Average     | 0.070   | 0.087   | 20.04           |

Figure 8: Clock errors between the static B2b-RTPPP and post-processing solutions.
(5.3×10^{-13} \text{ at } 120 \text{ s}), while it (9.9×10^{-15} \text{ at } 30720 \text{ s}) is worse than the B1I/B3I IF combination (6.5×10^{-15} \text{ at } 30720 \text{ s}) in the long term. Overall, for DF B2b-RTPPP time transfer, the B1I/B3I IF combinations are recommended.

To verify our previous conjecture that the impact of DCB on long-term frequency stability is greater than that on short-term frequency stability, we give a detailed analysis of the effect of DCB corrections on B2b-RTPPP time transfer, as shown below.

4.2.4. B2b-RTPPP time transfer without DCB corrections.

To test the influence of DCB corrections on B2b-RTPPP time transfer, the following experiment is proposed. Because the kinematic B2b-RTPPP time transfer performance without DCB corrections is too poor to be implemented due to the large pseudorange residuals of uncorrected pseudorange observations (see (5)), only the static B2b-RTPPP time transfer without DCB corrections is implemented. Figure 12 presents the clock errors between the static B2b-RTPPP solutions and the post-processing PPP solutions. The sequence of clock errors for B1I/B3I solution shows greater fluctuations than that of the B1C/B2a solution, with STDs of 0.377 ns and 0.121 ns, respectively, which is the opposite of B2b-RTPPP solutions with DCB corrections. We suspect that this may be due to two reasons. First, the pseudorange noise of the B1I/B3I combination is larger than that of the B1C/B2a combination due to the larger noise level of the B1I/B3I combination than that of the B1C/B2a IF combination. Second, the stability of the B1I-B3I DCB is 0.52 ns, approximately 1-2 times the STD of the B1Cp- and B2ap-B3I DCB (0.29 ns and 0.24 ns, respectively) [29].

In addition, Figure 13 displays the MDEV of the TLM2-USUD time link without DCB correction. On finding, it can be concluded that the MDEV of the B1C/B2a solution performs better than that of the B1I/B3I solution at different average times, further supporting our previous findings.

To further confirm our conclusions, the pseudorange residuals of the B1I/B3I and B1C/B2a IF combinations at the USUD station are depicted in Figure 14, where different colors represent different satellites. In Figure 14, the “DCB-corr” scheme means that the DCB is corrected in B2b-RTPPP time transfer, and the “non-corr” scheme means that the DCB is not corrected in the B2b-RTPPP time transfer. There are two findings highlighted here. First, the pseudorange residual of the B1I/B3I IF combination is greater than that of the B1C/B2a IF combination in the two schemes due to the larger noise level of B1I/B3I, which further suggests that the B1I-B3I DCB has worse accuracy than the B1C-B2a DCB. Second, there is a significant satellite-specific systematic bias with the “non-corr” scheme. Thus, the DCB should be corrected before using observation data of different signals; otherwise, a part of the DCB will be absorbed by the clock difference, reducing the B2b-RTPPP time transfer performance. Note that the DCB is not applied for the B3I signal because the B3I signal is taken as a frequency reference for BDS-3. In addition, the daily variation in the BDS-3 visible satellite number with the PPP-B2b corrections and position dilution of precision (PDOP) of four stations at a cut-off elevation angle of 7° is shown in Figure 15. It is found that the PDOP values of the CUSV and GUA1 stations changed more dramatically than those of the TLM2 and USUD stations. This is because the CUSV and USUD stations are located in relatively remote areas that can be covered by PPP-B2b service, so the number of satellites with PPP-B2b corrections is relatively small. Thanks to the completion of the BDS-3 constellation, the number of BDS-3 visible satellites in the territory of China has increased significantly. Hence, it is more important for DCBs to make reasonable corrections when using the PPP-B2b service.
Figure 10: Clock errors between the kinematic B2b-RTPP and post-processing solutions.
Table 5: STDs for each time link (unit: ns). The improvement indicates the kinematic B2b-RTPPP time transfer performance using B1I/B3I combination compared with that of using the B1C/B2a combination in STD values.

| Time link  | B1I/B3I | B1C/B2a | Improvement (%) |
|------------|---------|---------|-----------------|
| SHA1-USUD  | 0.285   | 0.301   | 5.316           |
| TLM2-USUD  | 0.295   | 0.322   | 8.385           |
| GUA1-USUD  | 0.286   | 0.324   | 11.728          |
| CUSV-USUD  | 0.354   | 0.369   | 4.065           |
| Average value | 0.305 | 0.329 | 7.374 |

Figure 11: MDEV of kinematic PPP solutions for the TLM2-USUD time link.

Figure 12: Clock errors between static B2b-RTPPP and post-processing PPP solution without DCB correction for the TLM2-USUD time link.
Figure 13: MDEV of static B2b-RTPPP solutions without DCB correction for the TLM2-USUD time link.

Figure 14: Pseudorange residual of B1I/B3I and B1C/B2a IF combination with/without DCB at USUD station on DOY 86, 2022 (unit: m).
5. Conclusions

In this contribution, the observation data from the selected two iGMAS stations and three MGEX stations were collected, covering a period of two days of March 27 and March 28, 2022. The quality of the PPP-B2b products is first assessed with the GBM final product as a reference. Then, the BDS-3 B2b-RTPPP time transfer performance is evaluated. The conclusions are as follows.

1. Compared to the CNAV1 broadcast ephemeris, the quality of the PPP-B2b orbit performs better, and the sequence of PPP-B2b orbit error is much smoother. In addition, the RMSEs of the PPP-B2b orbit are 0.081 m, 0.165 m, and 0.107 m in the RAC directions, respectively. For clock offset, the accuracy of PPP-B2b clock offset has a significant improvement compared to that of the CNAV1 broadcast ephemeris. Its STD value is 0.08 ns.

2. In the case of B2b-RTPPP transfer, the type A uncertainty of the B2b-RTPPP solution is within 0.1 ns in static mode and approximately 0.32 ns in kinematic mode. The B1I/B3I solution has higher accuracy than B1C/B2a solution in static and kinematic modes.

3. In terms of frequency stability, the MDEV of the static B2b-RTPPP solution is comparable to the post-processing solution. The B1C/B2a combination has better short-term frequency stability than B1I/B3I, while the long-term frequency stability of B1C/B2a is worse due to the larger noise level of the B1I/B3I combination. Since PPP-B2b provides the DCB with the B3I signal as a reference, the incomplete correction of the DCB error has a greater effect on the long-term frequency stability for the B1C/B2a IF combination.

4. In addition, the contribution of DCB corrections to the B2b-RTPPP time transfer performance is also investigated to explain the above findings. The STD of the B2b-RTPPP solution with the "non-corr" scheme is worse than that with the "DCB-corr" scheme. The frequency stability of the B1C/B2a solution without DCB correction is better than that of the B1I/B3I solution at different average times.

![Figure 15](image-url) Satellite number (SN) and PDOP of the BDS-3 visible satellites with PPP-B2b corrections on DOY 86 and 87, 2022.
Therefore, improving the accuracy of the PPP-B2b DCB product should be a focus in the future.

Overall, the PPP-B2b service can provide sub-nanosecond time transfer service to users in and around China, which can meet the demand for high accuracy and short latency in timing field. However, improving the accuracy of the DCB product should be a focus in the future.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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