# Postprint: Study on Short-Term Performance Evaluation and Update Frequency of Real-Time Precise Clock Offsets for PPP-B2b

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**Date:** 2023-06-07T00:00:00+00:00

## Abstract

This study investigates the short-term characteristics and prediction performance of PPP-B2b precise clock errors, and discusses the feasibility of relaxing the broadcast interval of precise clock error corrections. The results show that BDS-3 satellite onboard clocks and GPS BLOCK IIF onboard rubidium clocks exhibit good short-term frequency stability, with clock error prediction errors of approximately 1 cm at 120 s. The prediction errors have almost no impact on the convergence speed and post-convergence accuracy of Precise Point Positioning (PPP). In contrast, GPS BLOCK IIR satellite onboard clocks and satellite-borne cesium clocks demonstrate poor short-term performance, with 30 s prediction errors already reaching 4–6 cm, requiring high solution and update frequencies to meet user application requirements. The study finds that for satellites equipped with high-performance atomic clocks, the update cycle of clock error corrections can be appropriately extended to within 1 min without increasing user information acquisition time (which would increase with more broadcast information), thereby conserving downlink resources to broadcast more system products, atmospheric corrections, and other information, ultimately achieving service performance enhancement.

## Full Text

## Preamble

**ChinaXiv Cooperative Journal, Vol. 40, No. 4**

**December 2022**

**PROGRESS IN ASTRONOMY, Vol. 40, No. 4, Dec. 2022 doi: 10.3969/j.issn.1000-8349.2022.04.08**

# Research on Short-term Performance and Update Frequency of PPP-B2b Real-time Precise Clock Differences

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## Abstract

This study investigates the short-term characteristics and prediction performance of PPP-B2b precise clock differences, and discusses the feasibility of relaxing the broadcast interval for precise clock correction parameters. The results demonstrate that BDS-3 satellite clocks and GPS BLOCK IIF rubidium clocks exhibit excellent short-term frequency stability, with 120-second prediction errors of approximately 1 cm that have negligible impact on precise point positioning (PPP) convergence speed and post-convergence accuracy. In contrast, GPS BLOCK IIR satellite clocks and satellite cesium clocks show poor short-term performance, with 30-second prediction errors already reaching 4–6 cm, requiring high solution and update frequencies to meet user accuracy demands. The study finds that for satellites equipped with high-performance atomic clocks, the update period for clock correction parameters can be appropriately extended to within 1 minute without increasing user information acquisition time (which would otherwise increase with more broadcast information), thereby conserving downlink resources to broadcast additional system products and atmospheric corrections and achieving enhanced service performance.

**Keywords:** BeiDou-3 Navigation Satellite System; satellite precise clock difference; PPP-B2b service

**Classification Number:** P228

**Document Code:** A

## 1 Introduction

In the field of high-precision GNSS positioning, Precise Point Positioning (PPP) technology can provide users with accurate coordinates without reference stations and is widely applied in scientific domains such as ocean surveying and seismic early warning. PPP utilizes precise orbit and clock products typically provided by IGS analysis centers, with GPS, GLONASS, Galileo, and BeiDou-2 system satellite clock consistency of 2 cm, 5 cm, 5 cm, and 10 cm, respectively. However, these products generally suffer from several days of delay. With expanding GNSS applications, users in many fields demand higher real-time performance for precise products, such as low Earth orbit satellite orbit determination, UAV photogrammetry, and GNSS meteorology.

The BeiDou-3 System (BDS-3) provides the Precise Point Positioning Service (PPP-B2b), offering static centimeter-level and dynamic decimeter-level dual-system real-time PPP services for China and surrounding regions, representing one of BDS-3's distinctive services. PPP-B2b broadcasts real-time BDS-3 and GPS satellite precise orbit and clock correction products via GEO satellites in the BDS-3 constellation. Using the B2b correction products from GEO satellites and navigation messages from IGSO and MEO satellites, users can obtain PPP-B2b precise clock products with accuracy better than 0.3 ns.

In addition to PPP-B2b, multiple institutions currently provide real-time and near-real-time precise products. Table 1 shows the update intervals and accuracy of precise clock products from some institutions. To ensure clock product accuracy and meet the demands of high-frequency users, all real-time precise clock products, including PPP-B2b, employ second-level, high-frequency update and broadcast modes. However, unlike most real-time precise products distributed via the internet, PPP-B2b uses satellite downlink signals for broadcasting with a limited downlink rate of only 500 bit/s (25% of QZSS-CLAS). Currently, PPP-B2b only broadcasts precise products for BDS-3 and GPS dual systems. Among the four correction types—satellite mask, orbit corrections, clock corrections, and code bias—high-frequency clock corrections occupy approximately 50% of downlink resources.

With the current clock correction update cycle and downlink rate unchanged, PPP-B2b has no spare resources to broadcast clock corrections for Galileo or GLONASS systems to achieve four-system augmentation services. Moreover, adding tropospheric delay corrections or other parameters would significantly increase user data retrieval time (TTDR). Four-system augmentation and atmospheric correction broadcasting can effectively reduce user convergence time and improve positioning accuracy. Therefore, addressing the substantial occupation of downlink resources by high-frequency clock updates is a critical issue for further enhancing PPP-B2b service performance.

With the advancement of GPS modernization and the construction of emerging satellite navigation systems like BDS-3, satellite atomic clock performance has improved significantly. The excellent short-term performance of new onboard atomic clocks provides the possibility for reduced-frequency broadcasting of PPP-B2b precise clock products. This paper aims to evaluate the short-term frequency stability and prediction performance of PPP-B2b satellite precise clock differences solved using only the Chinese regional observation network, discuss the feasibility of adopting more flexible methods for broadcasting PPP-B2b precise clock products, and explore the possibility of using remaining broadcast resources to enhance PPP-B2b service performance.

This paper first briefly introduces the current status of PPP-B2b precise clock products, then evaluates their short-term performance and analyzes the positioning performance of predicted clock differences, and further discusses the update cycle and service accuracy of PPP-B2b precise clock products.

## 2 PPP-B2b Service Precise Product Calculation and Broadcast Cycle

The current PPP-B2b clock correction product solution flow is shown in Figure 1 [Figure 1: see original paper]. The orbit determination module injects the obtained satellite precise orbit into the clock estimation module, which fixes the precise orbit for real-time precise clock filter estimation. The correction calculation module then performs rational outlier removal and corrections based on precise products to compute the final correction products.

Due to objective constraints, the clock estimation module currently only uses observation data from the domestic regional network in China, and satellite clock differences can only be solved during satellite visibility periods. PPP-B2b currently employs a combined mode of hourly filter estimation and real-time filter estimation for real-time clock difference solutions. Hourly filter estimation injects solved ambiguity and troposphere information into the real-time filter estimation process every hour, ensuring stable convergence of the real-time filter estimation process without solution failure or service interruption as satellites continuously enter and exit the service area.

PPP-B2b broadcasts four types of correction products to users at a downlink rate of 500 bits per second. Type 1 provides a list of service satellites with a 48-second update cycle. Types 2 and 3 broadcast orbit corrections and DCB parameters for all in-view service satellites, also with a 48-second update cycle. Type 4 broadcasts clock corrections for all satellites in the mask list, using placeholders for out-of-view or invalid satellites, with a 6-second update cycle. PPP-B2b's TTDR is approximately 24 seconds, meaning users require 24 seconds to receive complete correction information for all satellites. Table 2 shows the typical message arrangement within 24 seconds:

(1) Within each 6-second cycle, clock corrections occupy 3 subframes (3 seconds), leaving remaining resources for other data types. Therefore, with the current broadcast cycle and mode unchanged, the downlink resources cannot support clock corrections for additional system satellites.

(2) Other data types require approximately 12 subframes per 48-second update cycle (depending on the number of valid in-view satellites), taking about four 6-second cycles. Adding tropospheric delay corrections or other parameters would directly increase TTDR.

## 3 PPP-B2b Satellite Clock Short-term Performance Analysis

Considering that satellite precise clock short-term performance relates to atomic clock type and may be affected by orbit errors, BDS-3 and GPS satellites are each divided into four categories for separate discussion. Table 3 shows the orbit types and atomic clock status for each satellite category.

### 3.1 PPP-B2b Clock Short-term Frequency Stability Analysis

For satellite clock differences, frequency stability does not reflect correctness but rather frequency consistency. Allan deviation and Hadamard deviation evaluate frequency stability considering first-order and second-order effects, respectively. Since this analysis focuses only on short-term stability where clock drift effects are negligible, Allan deviation is used to evaluate the stability of each satellite clock, providing a reference for subsequent prediction performance analysis.

Figure 2 [Figure 2: see original paper] shows the Allan deviation of PPP-B2b precise clock differences for various BDS-3 satellites. No significant differences exist in short-term stability among different satellite types. The ten-second stability is approximately $10^{-12}$, the hundred-second stability ranges between 2$×10^{-13}$ and 3$×10^{-13}, andthethousand−secondstabilityisabout1×10{-13}$. The Allan deviation curve slope gradually increases from -0.7 to -0.8 at ten seconds to -0.5 to -0.6, indicating that noise components in clock differences transition from phase white noise dominance to frequency white noise dominance. Generally, frequency white noise and frequency random walk noise dominate atomic clock ground measurements, while phase white noise primarily originates from residuals of satellite observation noise after adjustment in satellite clock differences.

Figure 3 [Figure 3: see original paper] shows the Allan deviation of PPP-B2b satellite clock differences for different GPS satellite types. Significant differences exist in short-term stability among different satellite types. Block IIF and Block III rubidium clock satellites demonstrate significantly better short-term stability than other types, with ten-second stability around 3$×10^{-12}, hundred−secondstabilitybetween3×10{-13}$ and 4$×10^{-13}, andthousand−secondstabilityof1×10{-12}$ to 2$×10^{-12}, slightlyinferiortoBDS−3satellites.BlockIIFcesiumclo
12}, hundred−secondstabilityaround1×10^{-12}, andthousand−secondstabilitybetween6×10{-13}$ and 9$×10^{-13}.BlockIIRandBlockIIR−Msatelliteshaveten−secondstabilitysimilartoIIFataround3×10{-12}, butexhibitnon−linearchangesinAllandeviationcurvesbetweentenandhundredseconds, withhundred−secondstabilityof1×10^{-12}$ to 2$×10^{-12}$ and thousand-second stability between 2$×10^{-13}$ and 4$×10^{-13}$, worse than Block IIF and BDS-3 satellites.

Notably, Block IIR and Block IIR-M satellites show obvious non-linear changes in Allan deviation between ten and hundred seconds. Li et al. studied the ultra-short-term stability of GPS satellite clock differences using high-frequency observations and observed similar non-linear changes without further analysis. The cause of this phenomenon remains unclear but will likely negatively impact prediction performance for corresponding time periods.

In summary, based on short-term stability, satellites can be roughly divided into two categories: the first includes all BDS-3 satellites and GPS new-model rubidium clock satellites (including Block IIF and Block III) with good short-term stability; the second includes GPS old-model satellites and Block IIF cesium clock satellites. The short-term stability differs significantly between the two categories, with the first clearly superior.

### 3.2 PPP-B2b Satellite Clock Prediction Performance Analysis

Satellite clock differences can be predicted using models such as linear polynomial, quadratic polynomial, or grey models. Since only short-term performance is analyzed, this section selects a simple linear polynomial model for short-term prediction of clock difference sequences, with a fitting duration of 2 minutes and prediction duration of 0–2 minutes. Prediction performance is evaluated by comparing differences between predicted and actual clock differences.

Figure 4 [Figure 4: see original paper] shows the prediction root mean square error (RMS) for different types of BDS-3 satellite clock differences. The prediction error trends are nearly linear, with consistent accuracy degradation over time. Except for individual satellites, the RMS of 1-minute predicted clock differences is better than 6 mm (0.02 ns), and the RMS of 2-minute predicted clock differences is better than 1 cm (0.033 ns).

Figure 5 [Figure 5: see original paper] shows the prediction errors for different types of GPS satellite clock differences. Different GPS satellite types exhibit different prediction accuracies. IIF rubidium clock satellites and IIIA satellites show no significant difference in clock prediction accuracy, achieving the highest accuracy among GPS satellites with linear degradation over time. The RMS of 1-minute predicted clock differences is 5–7 mm, and the RMS of 2-minute predicted clock differences is better than 11 mm, slightly worse than BDS-3 satellites. For Block IIR and IIR-M satellites, except PRN05, the RMS of 1-minute predicted clock differences is 4–6 cm, and the RMS of 2-minute predicted clock differences is 6–9 cm, differing by an order of magnitude from new-model GPS and BDS-3 satellites. Block IIF cesium clock satellites show the poorest prediction accuracy, with PRN08 and PRN24 satellites having 1-minute prediction RMS of 6 cm and 8 cm, respectively, and 2-minute prediction RMS reaching 8 cm and 12 cm.

Table 4 provides 30-second, 60-second, and 120-second prediction errors for each satellite type. Overall, new-model GPS satellites and BDS-3 satellites show consistent clock prediction performance, with 2-minute prediction RMS of approximately 1 cm. Since a linear polynomial model is used for prediction, only zero-order and first-order clock correction information needs to be included in broadcast messages, and the validity period of single-group clock corrections can reach at least 120 seconds. Block IIR, IIR-M, and Block IIF cesium clock satellites show poor prediction capability, with 30-second prediction errors already reaching 4–6 cm, requiring high solution and update frequencies to meet user accuracy demands and constraining the broadcast frequency of precise products.

## 4 PPP-B2b Predicted Clock Positioning Performance Analysis

In PPP, clock errors may affect positioning results differently depending on constellation geometry and other factors. To discuss the impact of clock prediction errors on positioning performance, dynamic PPP comparative experiments were conducted using GFZ products, PPP-B2b products, and PPP-B2b 120-second prediction products. To reduce interpolation errors of orbit and clock differences on positioning, PPP runs from 01:00 to 23:00 daily. Positioning parameters are shown in Table 5 .

This section discusses dynamic PPP positioning results from two aspects: convergence time and post-convergence 95% error limit. Since all BDS-3 satellites have good short-term prediction capability, this chapter conducts positioning experiments for both BDS-3 single-system and dual-system scenarios to compare the impact of 120-second clock prediction errors on positioning performance under two conditions: using only new-model satellites and mixing new and old models.

### 4.1 BDS-3 Single-system Dynamic Positioning Results

All BDS-3 satellites have good short-term prediction capability, allowing BDS-3 single-system dynamic positioning results to discuss the impact of new-model satellite clock prediction errors on positioning performance. Table 6 shows the post-convergence accuracy of BDS-3 single-system dynamic PPP using different products. The 120-second clock prediction error of BDS-3 satellites has almost no impact on post-convergence positioning accuracy. Table 7 shows the convergence time of BDS-3 single-system dynamic positioning, with convergence criteria from the BeiDou navigation application service performance architecture. If horizontal positioning errors remain below 30 cm and vertical errors below 60 cm for 5 consecutive minutes, positioning is considered converged. The results show that clock prediction errors affect dynamic PPP convergence time by less than 1 minute and have almost no impact on post-convergence accuracy, consistent with the conclusion in Section 3 that BDS-3 satellite clock 2-minute prediction errors are negligible.

### 4.2 Dual-system Dynamic Positioning Results

Table 8 shows convergence time statistics for dynamic positioning using different products, with convergence criteria of horizontal errors below 20 cm and vertical errors below 40 cm for 5 consecutive minutes. The convergence time using GFZ products and B2b products is essentially consistent, with an average convergence time of 12 minutes. Comparing prediction products with B2b products, the average convergence time increases from 12 minutes to 21 minutes.

Table 9 shows the post-convergence accuracy of dual-system dynamic PPP using different products. GFZ post-processed products achieve the highest positioning accuracy, with multi-station, multi-day statistical results of 95% positioning errors of 5 cm horizontally and 10 cm vertically after convergence. Using B2b products, the 95% positioning errors after convergence are 6 cm horizontally and 11 cm vertically, similar to GFZ products. Using predicted clock differences, the 95% errors are 9 cm horizontally and 15 cm vertically, showing significant accuracy degradation.

Figure 6 [Figure 6: see original paper] shows the dual-system dynamic positioning results for STA01 receiver data on August 2 using 120-second predicted clock differences and B2b clock differences. Comparing the two positioning results confirms that 120-second clock prediction errors cause slower dynamic positioning convergence and reduced positioning accuracy but do not cause dynamic PPP divergence. Comparing with BDS-3 single-system dynamic positioning results, it can be concluded that high-precision prediction clock differences for new-model satellites ensure dynamic PPP does not diverge, while large prediction errors from GPS old-model satellites and Block IIF cesium clock satellites cause dispersion in positioning results and are the main reason for dual-system positioning accuracy loss and increased convergence time.

## 5 Discussion on Clock Update Cycle

The previous sections briefly introduced the current status of PPP-B2b downlink messages and discussed the short-term performance of PPP-B2b real-time clock differences based on regional network solutions. The results indicate that due to significant performance gaps between old and new satellite atomic clocks, PPP-B2b can adopt more flexible message broadcast modes under current limited downlink rates.

Sections 3 and 4 concluded that for new-model satellites, linear polynomial prediction errors can be maintained at approximately 1 cm for 2 minutes. Therefore, if zero-order and first-order correction information are broadcast simultaneously, the validity period of single-group corrections for these satellites can reach at least 1 minute, allowing the update cycle to be extended to any duration within 1 minute without exceeding the current TTDR. Even if users fail to receive corrections for a satellite for 2 consecutive minutes, using correction information including the first-order term can still yield precise clock products with approximately 1 cm prediction error. For old-model satellites with poor prediction capability, the clock correction update cycle should remain at the current 6-second interval, broadcasting only the zero-order term. Using this new strategy, the 24-second PPP-B2b update message arrangement can be maintained while saving 3–4 subframe positions per 24 seconds, as shown in Table 10 .

Under the new broadcast mode, each subframe can contain clock differences for 12 new-model satellites or 23 old-model satellites, with satellite types distinguished in message type 1. While maintaining unchanged TTDR, 3–4 additional subframe positions can be added every 24 seconds for new navigation system support or broadcasting atmospheric enhancement information. As the proportion of satellites equipped with high-performance atomic clocks increases, the new broadcast mode will demonstrate greater advantages.

## 6 Conclusion

This paper introduces PPP-B2b precise clock products, evaluates their short-term performance, and discusses the current B2b message update mode based on this performance. After briefly assessing stability and prediction capability and analyzing the positioning performance of predicted clock differences, the paper further explores the timeliness and broadcast frequency issues of precise clock products.

Based on short-term stability and prediction capability, PPP-B2b service satellites can be roughly divided into two categories. The first category includes BDS-3 satellites and GPS new-model rubidium clock satellites (Block IIF and Block III), which exhibit the highest clock stability and optimal prediction performance, with short-term stability significantly superior to other types and 120-second prediction errors of approximately 1 cm. The second category includes GPS old-model satellites (Block IIR and IIR-M) and Block IIF cesium clock satellites, with 120-second prediction errors exceeding 10 cm.

Subsequent precise point positioning experiments using 120-second predicted PPP-B2b precise clock differences show that for BDS-3 single-system dynamic positioning, clock prediction errors have almost no impact on positioning. For dual-system dynamic positioning, prediction errors cause increased post-convergence 95% positioning errors and longer convergence times. Therefore, prediction errors from GPS old-model satellites and Block IIF cesium clock satellites are identified as the main cause of dual-system positioning accuracy loss and increased convergence time.

Considering the significant performance gap between old and new satellite atomic clocks, PPP-B2b can adopt more flexible message broadcast modes under current limited downlink rates. For the first category (BDS-3, Block IIF, and Block III), broadcasting only zero-order and first-order clock correction information ensures single-group correction validity of at least 120 seconds. Reducing the broadcast frequency of these satellites to 24 seconds can save 3–4 seconds of downlink resources per 24 seconds while maintaining TTDR and positioning accuracy. The second category shows poor prediction capability, with 30-second prediction errors already reaching 4–6 cm, and long-term prediction of single-group corrections would affect positioning accuracy. Therefore, high solution and update frequencies must be maintained to meet user demands, and the current broadcast cycle should remain unchanged. As GPS, BeiDou, and other GNSS systems continue upgrading, onboard satellite clock short-term stability performance will further improve, and the new broadcast mode will demonstrate increasing advantages as the proportion of high-performance atomic clocks grows.

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*Note: Figure translations are in progress. See original paper for figures.*