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REVIEW

Python toolbox for BDS PPP-B2b and Galileo HAS decoding and its products performance validation

Lewen Zhao[1,2,3]

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Abstract

Precision Point Positioning (PPP) technology can achieve decimeter to centimeter level positioning accuracy, which is essential for applications in industries such as autonomous driving, modern agriculture, and drone logistics. The PPP-B2b service provided by BDS and the High Accuracy Service (HAS) offered by Galileo, capable of achieving decimeter-level accuracy without relying on ground communication networks or commercial augmentation corrections, presents substantial potential for various industries. However, challenges persist when users try to utilize and evaluate these corrections, such as the lack of open-source software capable of decoding these products and the absence of product archives necessary for such evaluations. To address these challenges, we present a comprehensive Python toolbox called NavDecoder, which can decode both PPP-B2b and Galileo HAS products and provide archived data in ASCII format, facilitating its application. We also evaluated the accuracy of the two products, using the root mean square (RMS) of signal-in-space range error as a metric, with final products from Wuhan University serving as a benchmark. The average RMS was found to be 1.0 m for GPS in PPP-B2b and 0.62 m for GPS in Galileo HAS. For BDS in PPP-B2b, the average RMS was 0.67 m, while for Galileo in HAS, it was 0.18 m. Then, the accuracy of PPP-B2b and Galileo HAS products were validated using both static and kinematic PPP. A forward Kalman filter was employed for static PPP, while a combined forward and backward filter was used for kinematic PPP. The results demonstrate that comparable accuracy can be achieved through two positioning modes. BDS PPP-B2b offers superior positioning accuracy compared to Galileo HAS. Both products achieve an accuracy of 0.1 m with hourly PPP, with 4-hour observation periods yielding the most significant accuracy improvements.

Keywords Precise point positioning · PPP-B2b · Galileo · High accuracy service · Open source

Introduction

Real-Time Kinematic (RTK) positioning technology can achieve rapid, centimeter-level high-precision positioning. However, its quick positioning capability relies on a dense network of ground reference stations, ground communication network support, and two-way communication with users for broadcasting corrections. Consequently, the server's computational burden increases with the number of users. In contrast, Precise Point Positioning (PPP) (Zumberge et al. 1997) technology can achieve high-precision positioning globally with just a single station. With the availability of the International GNSS Service (IGS) real-time service (RTS) (Elsobeiey et al. 2016), it is now possible to achieve real-time PPP (RTPPP) using the precise satellite orbit and clock corrections. The performance of the products provided by various Multi-GNSS Experiment (MGEX) analysis centers has been validated, demonstrating that their accuracy meets the application needs of most users (Li et al. 2022).

However, RTPPP based on RTS still requires the support of terrestrial 4G and 5G networks, and communication delays often affect the positioning accuracy of real-time PPP. In contrast, China's BDS-3 provides real-time corrections

✉ Lewen Zhao
lwzhao@nuist.edu.cn

1 School of Remote Sensing and Geomatics Engineering, Nanjing University of Information Science and Technology, Nanjing, Jiangsu 210044, China

2 Technology Innovation Center for Integration Applications in Remote Sensing and Navigation, Ministry of Natural Resources, Nanjing, Jiangsu 210044, China

3 Jiangsu Province Engineering Research Center of Collaborative Navigation/Positioning and Smart Application, Nanjing, Jiangsu 210044, China

via the GEO (Geostationary Earth Orbit) satellites' B2b signal (PPP-B2b) (China Satellite Navigation Office 2020). According to the design, the structure of the BDS-3 PPP-B2b signal can encode State Space Representation (SSR) corrections for BDS, GPS, GLONASS, and Galileo. However, currently, only SSR corrections for BDS-3 and GPS are broadcasted for users in and around China. Additionally, the High-Accuracy Service (HAS) provided by Galileo's E6-B(European Union 2022) signal offers corrections for standard global PPP service and regional rapid positioning service. Relevant scholars have analyzed the availability and accuracy of correction products provided by both products, demonstrating that after a certain convergence time, they can meet decimeter to centimeter-level positioning accuracy (He et al. 2023; Nie et al. 2021; Tao et al. 2021; Naciri et al. 2023; Hauschild et al. 2022).

The formats of the messages received by PPP-B2b and Galileo HAS differ from the standard Radio Technical Commission for Maritime Services (RTCM) format due to restrictions on baud rate and ensuring the completeness of the broadcast corrections. For PPP-B2b messages, each message is 486 bits long and is encoded into 972 symbols using 64-ary Low Density Parity Check (64-ary LDPC). After LDPC decoding and CRC, the PPP service information can be extracted. For Galileo HAS, a high-parity vertical reed-solomon (HPVRS) encoding scheme is adopted (Fernández-Hernández et al. 2020), the decoding procedure is also required to recover the HAS corrections.

To support the decoding of raw messages for the evaluation and application of real-time augmented PPP services, researchers have developed various open-source tools. Horst et al. (2022) introduced an open-source Python-based HAS decoder named HASlib. Further research has also concentrated on decoding Galileo HAS and integrating it with open processing packages (Prol et al. 2024; Borio et al. 2023; Zhang et al. 2024). Additionally, Hirokawa provided a comprehensive Python tool called CSSRlib(Hirokawa et al. 2023), capable of performing RTK and PPP/PPP-RTK positioning using Receiver Independent Exchange Format (RINEX) (Gurtner et al. 2007) or correction data formatted in Compact SSR format. Moreover, an open-source software-defined radio (SDR) receiver was provided by Takasu (Ozeki et al. 2023; Tomoji 2022), which offers functionality for decoding GNSS raw messages from satellites. However, the decoding modules in these two packages are not specifically designed for satellite-based PPP augmentation information, and the decoding of PPP-B2b has not been thoroughly demonstrated.

In response to these limitations, we have developed a Python-based toolkit, partially leveraging functions from CSSRlib and pocketSDR, to decode PPP-B2b and Galileo HAS messages. The decoded corrections are saved in a format compatible with the corrections format from BKG Ntrip Client (BNC) software (Weber et al. 2007), and an archive in plain ASCII format is provided for users to quickly assess the performance of these corrections. The remaining sections are organized as follows: first, we introduce the details of the decoder toolkit, outlining its flow and characteristics; next, we evaluate the performance of the decoded orbits and clocks using final products from Wuhan University as a reference; finally, we assess the performance of both static and kinematic PPP.

Workflow

NavCm is the in-house software designed to support both real-time and post-processing PPP and RTK applications. A key component, NavDecoder, is responsible for decoding various correction formats, including RTCM, Galileo HAS, and BDS PPP-B2b, to recover the plain format of the corrections for simulated real-time processing or to feed the real-time engine. The architecture of the NavDecoder is shown in Fig. 1.

The module starts with downloading navigation messages in RINEX 3.X and RINEX 4.X formats, as well as real-time product archives from Centre National d´Etudes Spatiales (CNES) and rapid products from Wuhan University. These downloads are essential for evaluating the accuracy of PPP using satellite-based corrections, IGS MGEX real-time streams, and rapid products. Once the data is downloaded, the RINEX 3.X navigation files, together with Galileo HAS binary corrections, are used as inputs for the Galileo HAS decoder. Similarly, RINEX 4.X navigation files are used for BDS, where CNAV1 messages are processed along with PPP-B2b correction messages in the decoder.

In addition, two parameters, "max_age_clocks" and "max_age_orbits", must be configured to manage the synchronization of different types of corrections as well as the alignment between the corrections and the broadcast ephemeris. By default, PPP-B2b messages update clock corrections every 6 s and orbit corrections every 48 s, while for Galileo HAS, clock corrections are updated every 10 s, and orbit corrections every 50 s. Although these corrections are generally consistent, discrepancies may occur due to missing correction products or ephemeris IOD (Issue of Data) switches. To ensure the continuity of PPP positioning, the NavDecoder considers both the matching of IOD parameters and the stability of orbit and clock products. Missing corrections are specifically addressed within a 300-second window for orbits and a 60-second window for clocks, achieved by the default settings of max_age_clocks = 60 and max_age_orbits = 300.

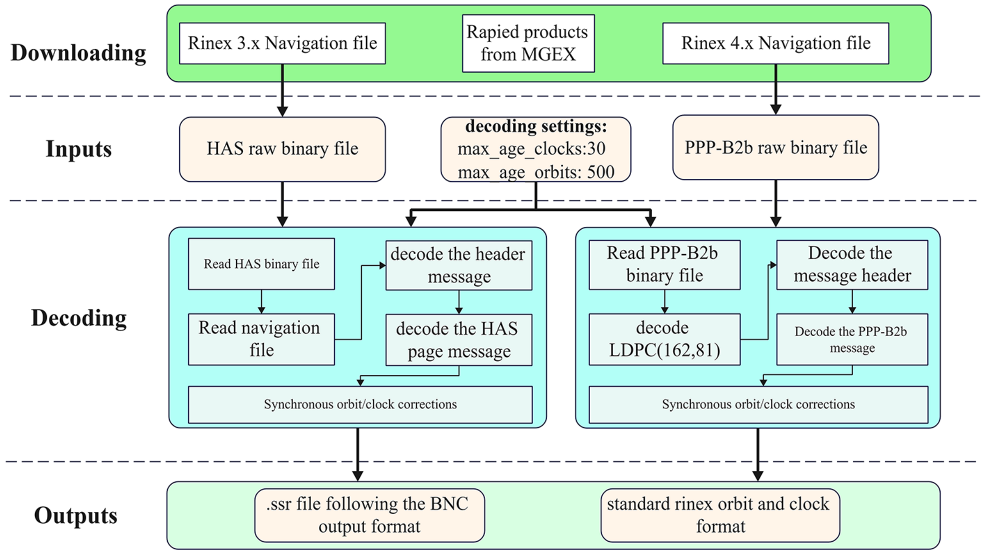


Fig. 1 Architecture of NavDecoder

Once the inputs are configured, the decoding process begins. The main decoding functions, which support the binary format of the "BDSRawB2b" block and the "GAL-RawCNAV" block from the Septentrio receiver and utilize components from CSSRLIB and Pocket-SDR libraries, have been reorganized for better integration, with some external code removed. The NavDecoder also supports decoding PPP-B2b plain text output from the Unicore receiver, addressing the fact that the raw messages from Septentrio do not decode the complex LDPC (162,81).

After decoding, the orbit and clock corrections with the matching epoch and IOD are synchronized, saving the data in a plain text format consistent with BNC message output. The system also supports plain ASCII formats for standard SP3 format. However, it is important to note that occasional gaps in the corrections for some satellites may occur. Users should account for these gaps when using SP3 format file for PPP, as interpolating the precise position across these gaps may introduce errors.

In summary, the key features of the NavDecoder are as follows:

1. Download tools for retrieving navigation and MGEX orbit/clock products.
2. Support for raw binary HAS data from Septentrio GNSS receivers: The system can be easily extended to support binary data from various manufacturers by extracting raw Galileo C/NAV data for input into the decoding function.
3. Support for PPP-B2b data from Septentrio and Unicore GNSS receivers: Septentrio provides raw binary format, which requires an LDPC decoder to recover plain corrections, while Unicore offers plain ASCII format that can be directly processed to recover corrections.
4. Capability to save corrections in the BNC universal format.
5. Capability to save corrections in SP3 format.
6. Provision of an archive for BDS PPP-B2b and Galileo HAS corrections.

Experiments and assessment

Signal-in-space range error assessment

The performance of the BDS PPP-B2b and Galileo HAS real-time correction messages was evaluated using the final GNSS precise orbit and clock data provided by Wuhan University as the reference. Figure 2 shows the time series of Signal-in-Space Range Error (SISRE) for GPS and BDS satellites from PPP-B2b products during days 075 to 174 of the year 2024. The observed gaps in the figure were caused by interruptions in data recording due to a temporary storage capacity issue or power failure. Data recording resumed once the issue was resolved. It is clear that the GPS SISRE errors are larger than those of BDS, with 98% of the averaged SISRE errors at 2.0 m for GPS and 1.7 m for BDS. There are also notable outliers in the GPS SISRE error series, with several satellites showing errors exceeding 6 m. Figure 3 presents the Root Mean Square (RMS) error of SISRE for each satellite. The average RMS values are 1.0 m for GPS and 0.67 m for BDS. Significant variations are observed among individual GPS satellites, whereas the RMS for BDS satellites is more consistent, primarily below 1.0 m.

In comparison, Fig. 4 presents the SISRE errors for GPS and Galileo satellites using Galileo HAS corrections. The HAS GPS corrections show fewer outliers compared to the PPP-B2b GPS corrections. Additionally, the SISRE also reveals systematic biases among different satellites, as

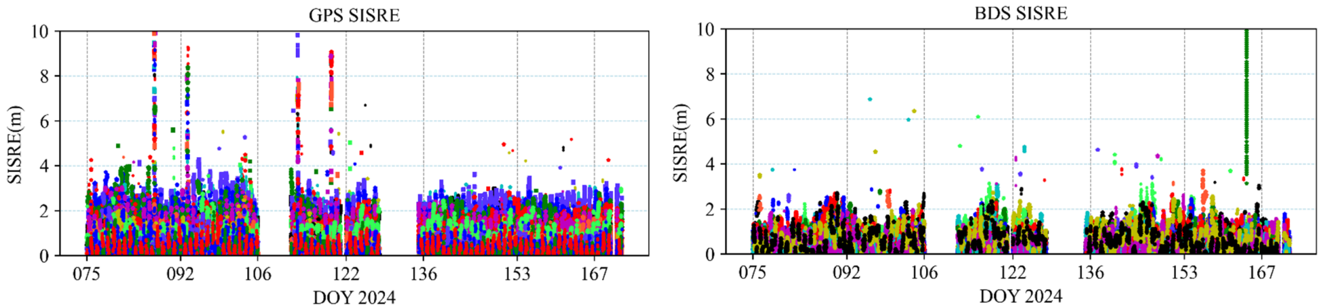


Fig. 2 The SISRE error time series for GPS and BDS from PPP-B2b with reference to WUM products. Different colors represent different satellites

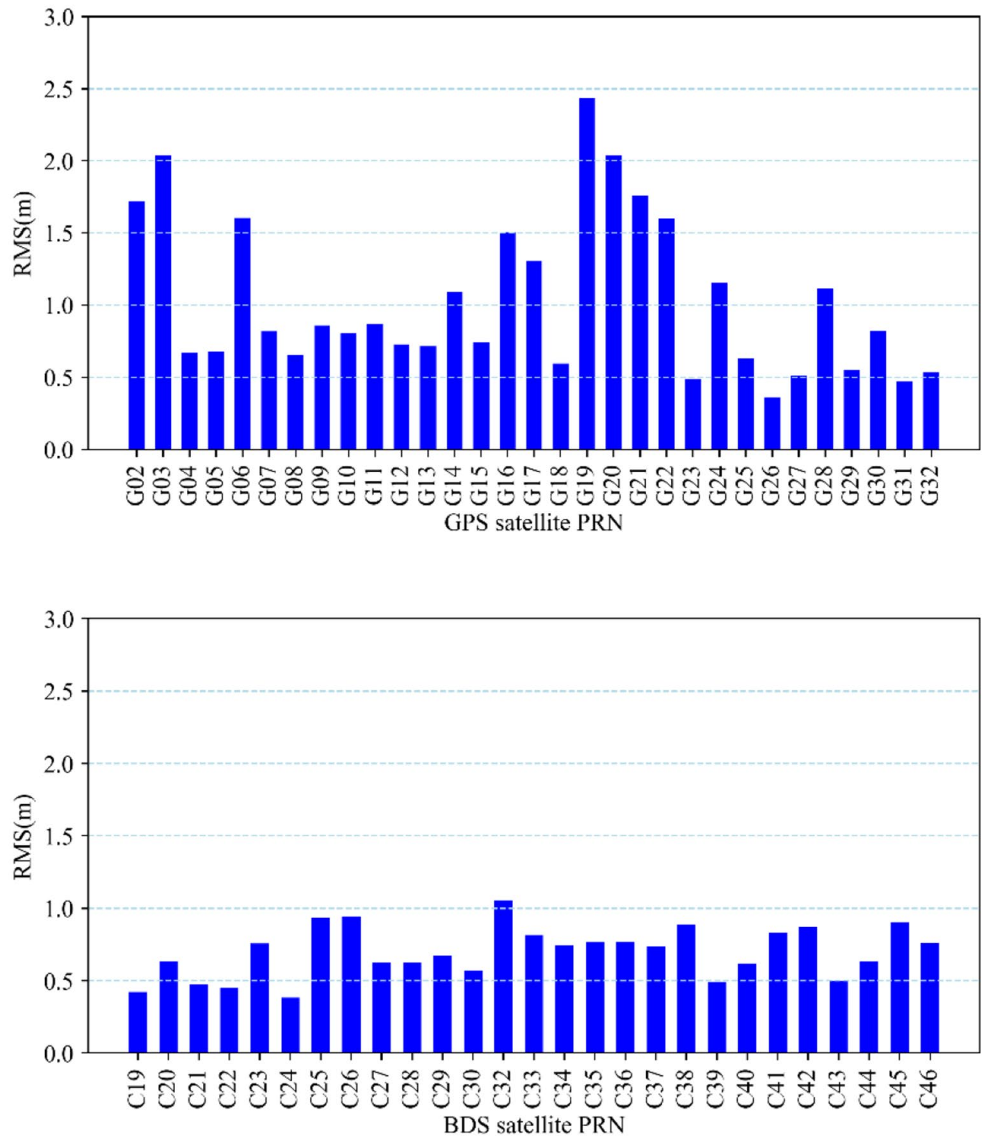


Fig. 3 The RMS of the SISRE errors for GPS and BDS from PPP-B2b products respectively

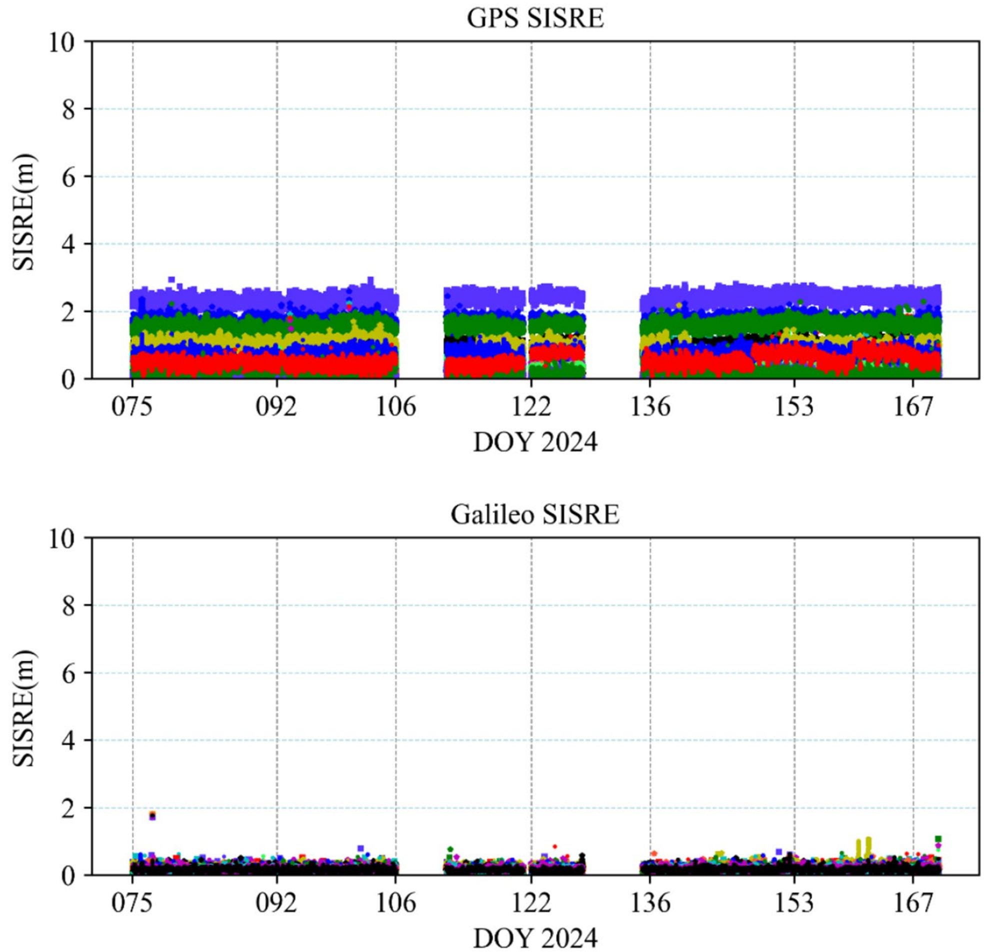


Fig. 4 The SISRE error time series based on HAS for GPS and GAL with reference to WUM products. Different colors represent different satellite

indicated by the RMS values in Fig. 5. The average RMS of SISRE values is 0.62 m for GPS, which is superior to the GPS product provided by PPP-B2b. Galileo satellites show smaller RMS values, averaging 0.18 m, and show good consistency across different satellites. Overall, the Galileo HAS GPS products demonstrate superior accuracy compared to the B2b products.

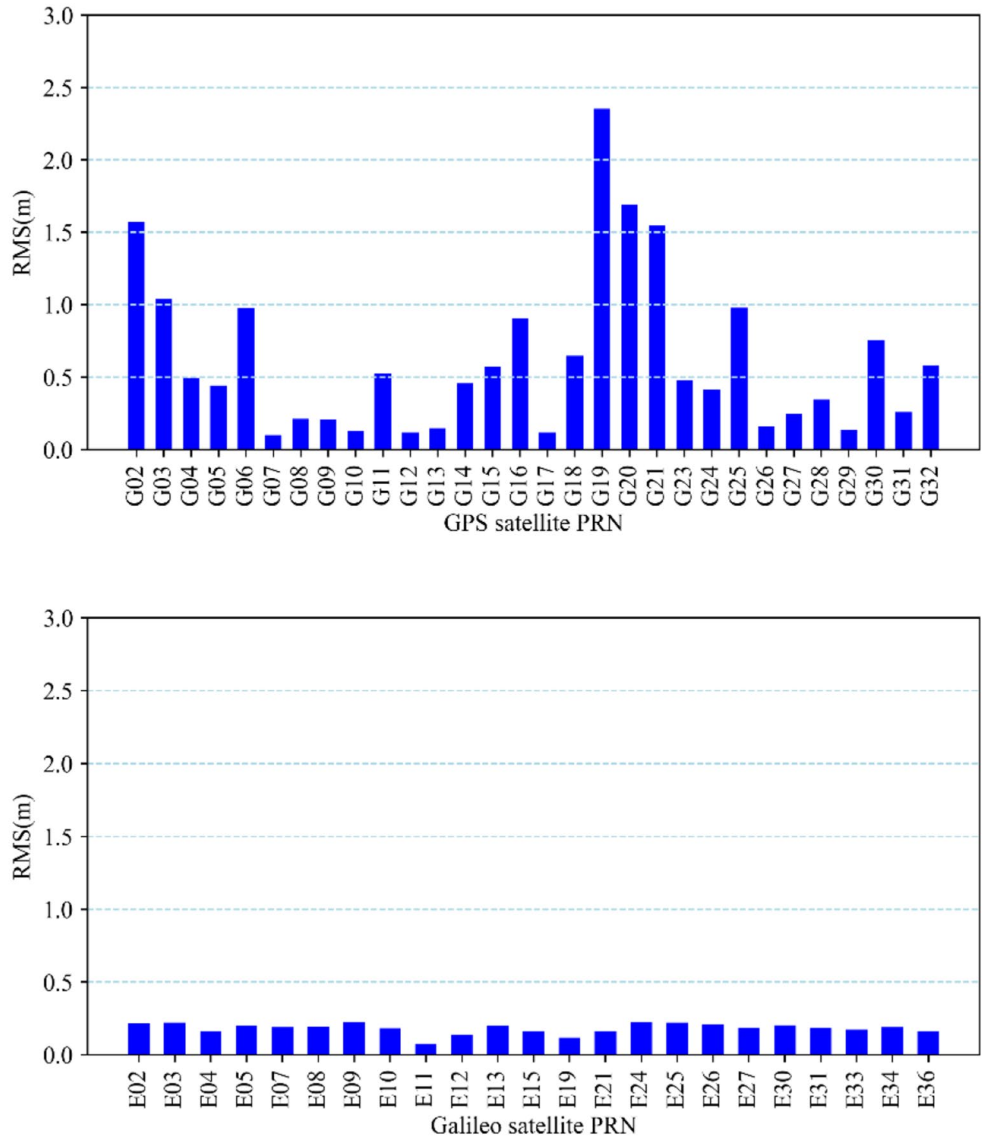
Static and kinematic PPP assessment

Galileo provides HAS service on a global scale. However, the orbit and clock corrections for PPP-B2b are transmitted by BDS-3 GEO satellites, with coverage primarily in the Asia-Pacific region. To compare the performance of these two products, PPP was calculated using MGEX stations located in the Asia-Pacific region, as shown in Fig. 6, with a data sampling rate of 5 s. All data were processed with a dual-frequency ionosphere-free combination. A forward Kalman filter and smoothing method were applied. The detailed strategies are outlined in Table 1.

Figure 7 illustrates the positioning accuracy and repeatability of static PPP in both horizontal and vertical directions over different observation durations using PPP-B2b products. The averaged RMS values are plotted as bars, with different colors representing different observation session lengths, whereas the repeatability, measured by the standard deviation, is shown as red error bars on the bar chart. Overall, as the observation durations increase, the positioning accuracy and repeatability of PPP improve significantly. For the hourly PPP solutions, the average positioning accuracy is 0.067 m and 0.071 m in the horizontal and vertical direction respectively. The horizontal accuracy improves to 0.059 m and 0.048 m for 2-hour and 4-hour solutions, representing improvements of 15% and 30%, respectively. Furthermore, with additional increases in processing length, the enhancement in horizontal positioning accuracy and repeatability persists but at a diminishing rate. The 6-hour, 12-hour, and 24-hour solutions achieve average accuracies of 0.046 m, 0.042 m, and 0.041 m, respectively. A similar trend is also visible in the vertical direction, with the average vertical positioning accuracy improving to 0.065 m and 0.056 m for the 2-hour and 4-hour solutions, respectively, achieving an average accuracy of approximately 0.05 m for observation periods of 12 h or more.

In contrast, Fig. 8 presents the performance of PPP based on the GPS and Galileo dual-system combination using the

Fig. 5 The RMS of the SISRE errors for GPS and Galileo from HAS products respectively



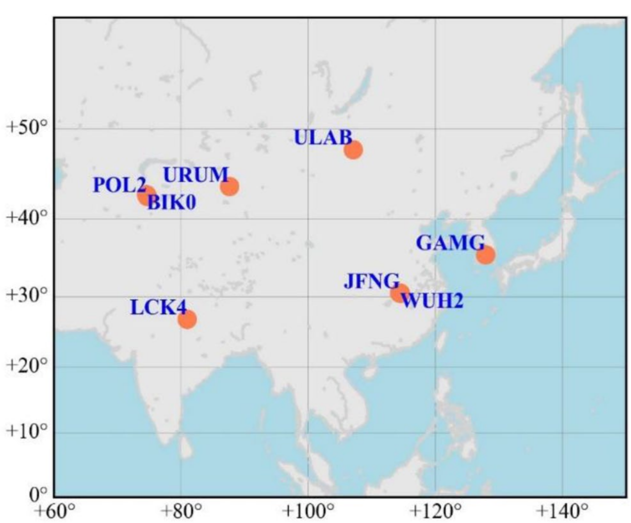


Fig. 6 MGEX stations used for PPP-B2b and Galileo HAS performance evaluation

Galileo HAS product, showing the positioning accuracy for various observation durations. For the hourly solution, the average positioning accuracies are 0.1 m in the horizontal direction and 0.079 m in the vertical direction. The vertical accuracy is better than the horizontal, primarily due to the relatively poor eastward accuracy, measured at 0.08 m, which is even lower than the vertical accuracy. The horizontal accuracy improves substantially with longer observation durations, reaching 0.089 m, 0.075 m, 0.068 m, 0.061 m, and 0.057 m for 2-hour, 4-hour, 6-hour, 12-hour, and 24-hour periods, respectively. Similarly, the vertical accuracy improves to 0.07 1 m, 0.063 m, 0.059 m, 0.053 m, and 0.049 m for the same durations. In comparison with PPP-B2b solutions, the Galileo HAS product's positioning accuracy is generally inferior in both horizontal and vertical directions.

Table 1 PPP strategies using PPP-B2b and Galileo HAS products

Items	PPP-B2b products processing strategies	Galileo HAS products processing strategies
Observation frequency	GPS: L1/L2 BDS: B1-2/B3	GPS: L1/L2 Galileo: E1/E5a
Satellite orbits/clocks	GPS: LNAV + PPP-B2b BDS: CNAV1 + PPP-B2b	GPS: LNAV + HAS Galileo: I/NAV + HAS
Weighting scheme	Elevation dependent weighting	
Elevation mask	7°	
Satellite antenna phase center	No correction	
Estimation method	Forward Kalman and backward smoothing	
Ionospheric delay	Ionosphere-free combination	
Tropospheric delay	Zenith wet delay is estimated as random walk noise process	
Ambiguities	Estimated as float constant	
Receiver clock and inter-system bias	Estimated as white noise	

We further analyze the positioning accuracy of dynamic PPP, which employs forward filtering followed by backward filtering to enhance accuracy during the convergence phase. Figure 9 presents the positioning accuracy and repeatability using PPP-B2b products across different observation durations. The analysis shows that the positioning accuracy of backward filtering is correlated with the observation duration. This is primarily because with increased convergence time, the tropospheric delay and ambiguity parameters estimated by PPP are continuously refined. Overall, a 1-hour dynamic PPP achieves a positioning accuracy of 0.072 m horizontally and 0.076 m vertically. As the convergence time increases, the 4-hour observation duration demonstrates significant improvements, with horizontal and vertical positioning accuracies improving to 0.043 m and 0.065 m, respectively. Further increases in convergence time result in limited accuracy improvements in dynamic PPP. Figure 10 shows the positioning accuracy using Galileo HAS products, with horizontal and vertical accuracies of 0.11 m/0.097 m, 0.098 m/0.1 m, and 0.086 m/0.1 m for 1-hour, 2-hour, and 4-hour durations, respectively.

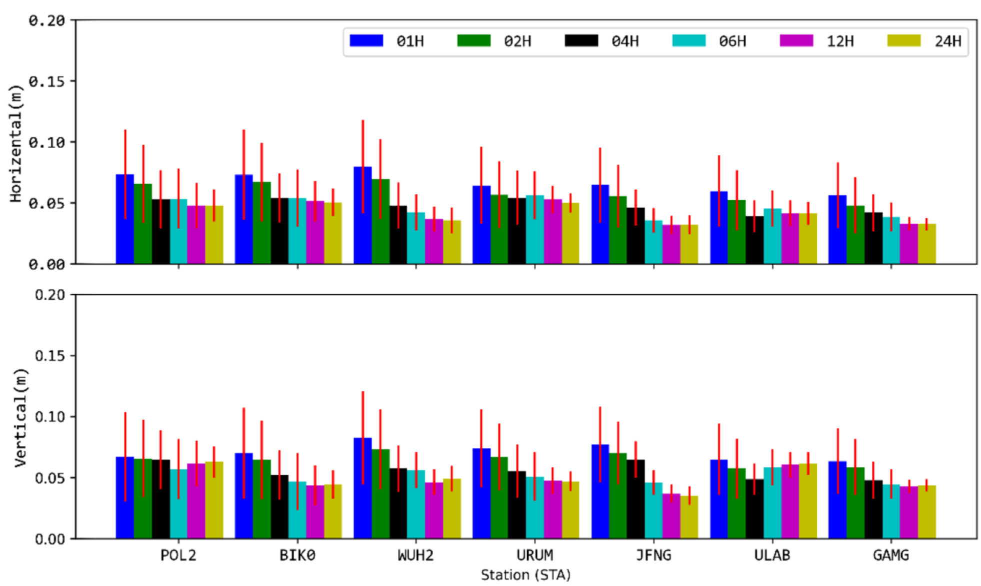


Fig. 7 Positioning accuracy and repeatability of static PPP using PPP-B2b across different observation durations

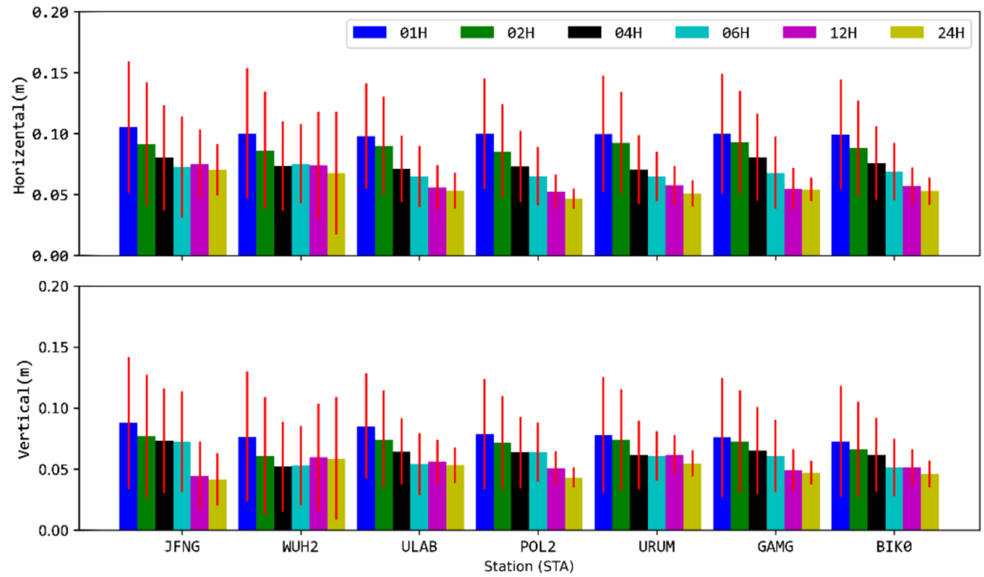


Fig. 8 Positioning accuracy and repeatability of static PPP using Galileo HAS across different observation durations

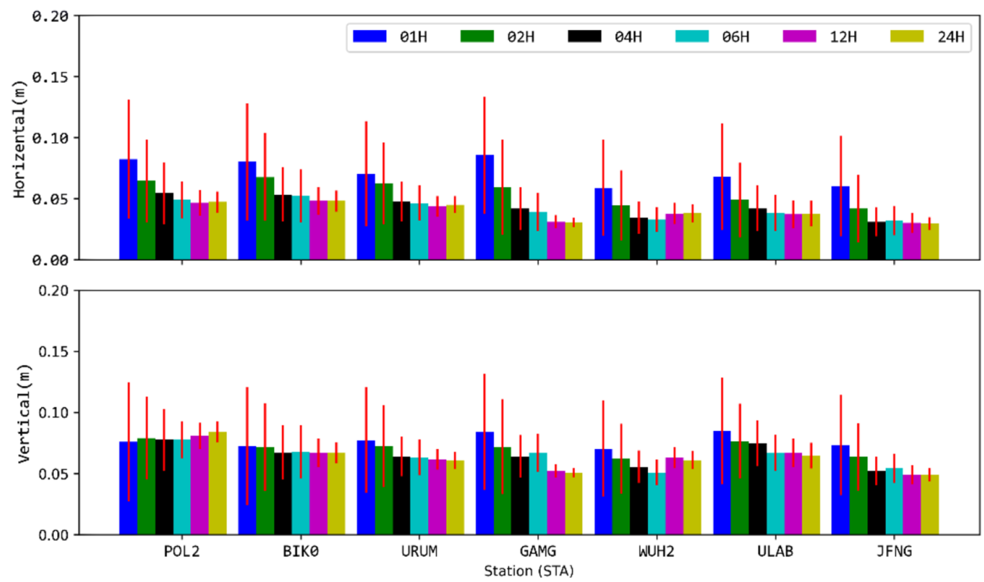


Fig. 9 Positioning accuracy and repeatability of kinematic PPP using PPP-B2b across different observation durations

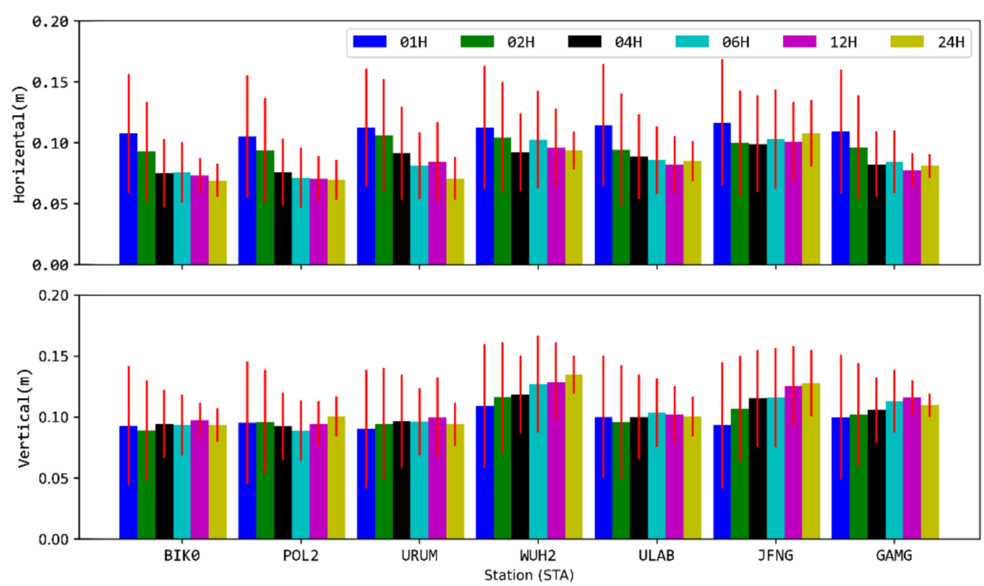


Fig. 10 Positioning accuracy and repeatability of kinematic PPP using Galileo HAS across different observation durations

Conclusion

The open services provided by BDS PPP-B2b and Galileo HAS enable decimeter- to centimeter-level positioning for a wide range of users, without the need for commercial augmentation. To facilitate the use of these services, a Python-based toolkit was developed to decode PPP-B2b and Galileo HAS messages, partially leveraging functions from CSSRlib and pocketSDR. The decoded corrections are saved in an ASCII format compatible with BNC software, allowing users to quickly assess the performance of these corrections.

Firstly, the performance of PPP-B2b and Galileo HAS corrections was evaluated using the final GNSS precise orbit and clock data from Wuhan University as the reference, with the SISRE employed as the metric to account for both orbit and clock errors. The results indicate that the PPP-B2b corrections yield average RMS values of 1.0 m for GPS and 0.67 m for BDS. In contrast, Galileo HAS demonstrated superior accuracy, providing an average RMS of 0.62 m for GPS and 0.18 m for Galileo satellites.

Subsequently, the performance of PPP was assessed using MGEX stations in the Asia-Pacific region, given that PPP-B2b is a locally based augmentation service. For static PPP, the results show that accuracies better than 0.1 m can be achieved with both PPP-B2b and Galileo HAS solutions using hourly static PPP. Extended observation periods further improve accuracy, with 4-hour durations yielding the most significant enhancements, achieving accuracies better than 0.05 m for BDS PPP-B2b and 0.08 m for Galileo HAS. To achieve an accuracy of 0.05 m in both horizontal and vertical directions, at least 12 h of observation are required. In kinematic PPP, accuracy comparable to that of static PPP can be achieved across varying observation durations through the use of backward smoothing.

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Author contributions L.Z. refined the python toolbox and write the manuscript.

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Data availability The Python toolbox and the archived PPP-B2b and HAS correction datasets can be found at https://github.com/NavSesne/NavDecoder.

Declarations

Ethical approval and consent to participate Not applicable.

Competing interests The authors declare no competing interests.

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