USER IMPLEMENTATION AND ASSESSMENT OF BDS-3 PRECISE POINT POSITIONING AUGMENTATION SERVICE WITH NO ECONOMIC COST

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ABSTRACT:

The satellite-based precise point positioning (PPP) service enables users with high accuracy positions without Internet connections. Currently, two types of satellite-based PPP services are available. One type is commercial service, such as Trimble CenterPoint RTX service. The second type is non-commercial and cost-free service, including the BDS-3 satellite-based PPP service based on PPP-B2b signals. This service is currently open access to all receiver manufacturers. This contribution firstly presents a detailed instruction on how to apply PPP-B2b signals into positioning. Afterwards, the performance of BDS-3 PPP service is validated with both static and kinematic experiments carried out in Wuhan, China, during day of year 168 and 172, 2022. Results indicate that PPP-B2b signals mainly improve BDS-3 clock precision and GPS orbit accuracy. With BDS-3 PPP-B2b augmentation messages, the static satellite-based PPP shows 3.9/6.9/10.3 mm daily solution repeatability in E/N/U directions, respectively. An average of 13.9 min convergence time and 3.42/2.16/6.65 cm E/N/U positioning accuracy are achieved in the simulated kinematic mode. During a 28-min stepper motor driven movement test, 3.48/14.88 cm 2D/3D kinematic positioning accuracy is obtained using the BDS-3 PPP service.

1. INTRODUCTION

Nowadays, there are mainly two approaches for PPP service delivery, i.e., ground-based internet communication and space-based satellite broadcasting. For services delivered by internet, users are required to equip with SIM cards and pay mobile subscription fees. IGS analysis centers (ACs) initialized the first real-time service (RTS) in 2013 (Caissy et al., 2013). State Space Representation (SSR) corrections are encoded into Radio Technical Commission for Maritime services (RTCM)-formatted messages (RTCM-SC, 2016), then sent to users through the Networked Transport of RTCM via Internet Protocol (NTRIP) (RTCM-SC, 2011).

As for satellite broadcasting PPP services, users are required to equip with specific GNSS antenna and receiver to implement satellite-based PPP. Nowadays, two types of satellite-based PPP services are available, i.e., commercial and non-commercial. For the commercial services, users are required to pay extra service subscription fee to access to L-band augmentation signals. These commercial satellite-based PPP services include CenterPoint RTX provided by Trimble, Atlas provided by Hemisphere, TerraStar provided by NovAtel, APEX provided by VERIPOS, MarineStar provided by FUGRO, Hi-RTP provided by Hi-Target, etc. Regarding the non-commercial service, users can access to augmentation messages at no economic costs. So far, three GNSSs provide non-commercial satellite-based PPP services, i.e., QZSS Centimeter-Level Augmentation Service (CLAS, L6 signal) (Namie et al., 2021), Galileo High Accuracy Service (HAS, E6B signal) (Fernandez-Hernandez et al., 2022) and BDS-3 PPP service (PPP-B2b signal) (Yang et al., 2022). Table 1 tabulated a summary of these two PPP service categories.

This study focuses on the BDS-3 PPP service which becomes available on 3 August 2020, along with the PPP-B2b signal Interface Control Document (ICD) (CSNO, 2020). The PPP-B2b signal construction mythology was first reported by Liu et al. (2020) and Liu et al. (2022a). The precise orbit and clock estimation strategy used by the service was first reported by Tang et al. (2022). SSR corrections provided by the service were assessed by several studies (Xu et al., 2021, Tao et al., 2021, Ren et al., 2021, Nie et al., 2021). Using the service, positioning performance of International GNSS Monitoring and Assessment System (iGMAS) and Multi-GNSS Experiment (MGEX) tracking station were presented by Liu et al. (2022b) and Yang et al. (2022). The long-term performance of BDS-3 PPP service was reported by Sun (2023) with 48-week data collected from 2021 to 2022. Comparing with GFZ final orbit, the radial accuracy of BDS-3 MEO, GPS, and BDS-3 IGSO satellites are 0.056 m, 0.069 m, and 0.172 m, respectively. Constant satellite-specific clock biases in different arcs of the satellite were identified. The STD of SISRE for BDS-3 MEO, GPS and BDS-3 IGSO are 0.059 m, 0.092 m and 0.174 m, respectively. Centimeter static and decimeter kinematic positioning accuracies were achieved by using 108-day observation data from 12 MGEX stations.

On the one hand, most previous studies validated the BDS-3 PPP service with independently collected PPP-B2b augmentation messages and BDS-3/GPS navigation messages. In other words, the augmentation and navigation signals were collected by two separate receivers, which is not the real situation when using the service. On the other hand, concrete BDS-3 PPP service usage was not fully introduced in previous studies. Considering the satellite-based and cost-free features,

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there exists great potentials to implement BDS-3 PPP service into mass-market applications. To facilitate better understanding of BDS-3 PPP service, we conduct a comprehensive investigation about the user implementation and assessment of BDS-3 PPP service using a single receiver and with no economic cost.

Firstly, the user implementation of BDS-3 PPP service is comprehensively introduced. Then, one consecutive five-day static and simulated kinematic experiment are carried out along with one 28-min stepper motor driven kinematic experiment in June 2022 in Wuhan, China. Performance of BDS-3 PPP service are assessed under both static and kinematic scenarios. Conclusions are summarized in the end.

Service delivery method	Hardware requirement	Service cost	Service provider	Representations
Ground-based internet communication	- GNSS Antenna and receiver -SIM card	Mobile data fee	IGS ACs	BKG, CNES, DLR, ESA, GFZ, GMV, NRCan, UPC, WHU, CAS, SHAO
Space-based satellite broadcasting	GNSS Antenna and receiver	Subscription fee	Commercial companies	Trimble (CenterPoint RTX), Hemisphere (Atlas), NovAtel (TerraStar), VERIPOS (APEX), FUGRO (MarineStar), Hi-Target (Hi-RTP)
		Free	**GNSS**	QZSS L6 (CLAS), Galileo E6B (HAS), **BDS-3 PPP-B2b (PPP service)**

Table 1. Classification of PPP services.

2. USER IMPLEMENTATION OF BDS-3 PPP SERVICE

Fig. 1 presents how BDS-3 PPP service is transmitted by PPP-B2b signals. First, SSR corrections are encoded into PPP-B2b augmentation messages. Then, the augmentation messages are modulated on PPP-B2b signals. In the end, the PPP-B2b signals are broadcast to ground users by BDS-3 GEO satellites.

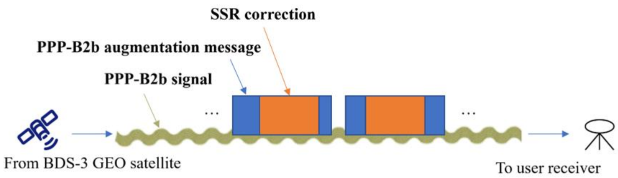

Figure 1. Relationship among PPP-B2b signal, PPP-B2b augmentation message and SSR correction.

As shown in Fig. 2, four steps are required to use the BDS-3 PPP service, i.e., decoding of PPP-B2b augmentation messages, issue of data (IOD) matching between PPP-B2b augmentation messages and broadcast ephemerides, broadcast satellite orbit/clock calculation based on broadcast ephemerides, and precise orbit/clock calculation based on PPP-B2b augmentation messages.

Step 1 Decoding of PPP-B2b augmentation messages

The target of step 1 is to extract SSR corrections from raw binary messages output by receiver. In current stage, five types messages are modulated into PPP-B2b signals, i.e., Type 1 (satellite masks), Type 2 (orbit corrections), Type 3 (DCB corrections), Type 4 (Clock corrections) and Type 63 (null message).

Step 2 IOD matching between PPP-B2b augmentation messages

Step 2 determines correct matching between decoded corrections and broadcast ephemeris. As of April 2023, only BDS-3 and GPS are supported by BDS-3 PPP service. Note that corrections provided by BDS-3 PPP service aim at BDS-3 CNAV1 and GPS LNAV ephemerides. The concrete message decoding and IOD matching procedure can refer to Ouyang et al. (2023).

Step 3 Broadcast satellite orbit/clock calculation

Once the IOD matching between PPP-B2b augmentation messages and broadcast ephemerides is achieved, users should subsequently calculate broadcast satellite orbit and clock offset based on BDS CNAV1 and GPS LNAV ephemerides, respectively. The satellite clock offset calculation algorithm is identical for both types of ephemerides. However, two differences exist in the BDS and GPS satellite orbit calculation algorithm.

The BDS CNAV1 adopts an 18-parameter model for orbit calculation (CSNO 2017), while GPS LNAV adopts a 16-parameter model (NCO 2021). Table 2 lists the parameter comparison between these two models. One difference is the semi-major axis-related parameter. BDS-3 CNAV provides two parameters (ΔA and $\dot{A}$) and GPS LNAV provide only one ($\sqrt{A}$). The second difference exists in the mean motion difference-related parameter. BDS-3 CNAV1 provides Δn_0 and $\Delta \dot{n}_0$, while GPS LNAV provides Δn . Table 3 presents the orbit calculation algorithm comparison between BDS-3 and GPS. It is clear that BDS-3 CNAV1 and GPS LNAV ephemerides have different equations for satellite semi-major axis and corrected mean motion calculation.

Step 4 Precise satellite orbit/clock calculation

Precise satellite orbit is calculated as:

$$X_{brdc+SSR\ 3\times1} = X_{brdc\ 3\times1} - \delta X_{3\times1} \quad (1)$$

$$\delta X_{3\times1} = [e_{radial} \quad e_{along} \quad e_{cross}]_{3\times3} \bullet \delta O_{3\times1} \quad (2)$$

$$e_{radial\ 3\times1} = \frac{r_{3\times1}}{|r|} \quad (3)$$

$$e_{cross\ 3\times1} = \frac{r_{3\times1} \times \dot{r}_{3\times1}}{|r \times \dot{r}|} \quad (4)$$

$$e_{along\ 3\times1} = e_{cross\ 3\times1} \times e_{radial\ 3\times1} \tag{5}$$

where $X_{brdc+SSR}$ and X_{brdc} are precise and broadcast satellite coordinates, respectively; δX denotes the orbit correction vector under Earth-centered, Earth-fixed (ECEF) coordinate system; δO is the orbit correction vector extracted from PPP-B2b augmentation messages; r and $\dot{r}$ stand for satellite position and velocity vectors based on broadcast ephemeris; e_{radial}, e_{along} and e_{cross} stand for unit vectors corresponding to satellite R, A and C directions. It should be noted that the formula of e_{radial}, e_{along} and e_{cross} are not identical to those used in IGS RTS (Shi et al., 2015, 2019; Ouyang et al., 2021).

Precise satellite clock offset is calculated as:

$$dt^{s}_{brdc+SSR} = dt^{s}_{brdc} - \frac{C_0}{c} \tag{6}$$

where $dt^{s}_{brdc+SSR}$ is the precise satellite clock offset; dt^{s}_{brdc} denotes the broadcast satellite clock offset; C_0 stands for clock correction extracted from the PPP-B2b augmentation message.

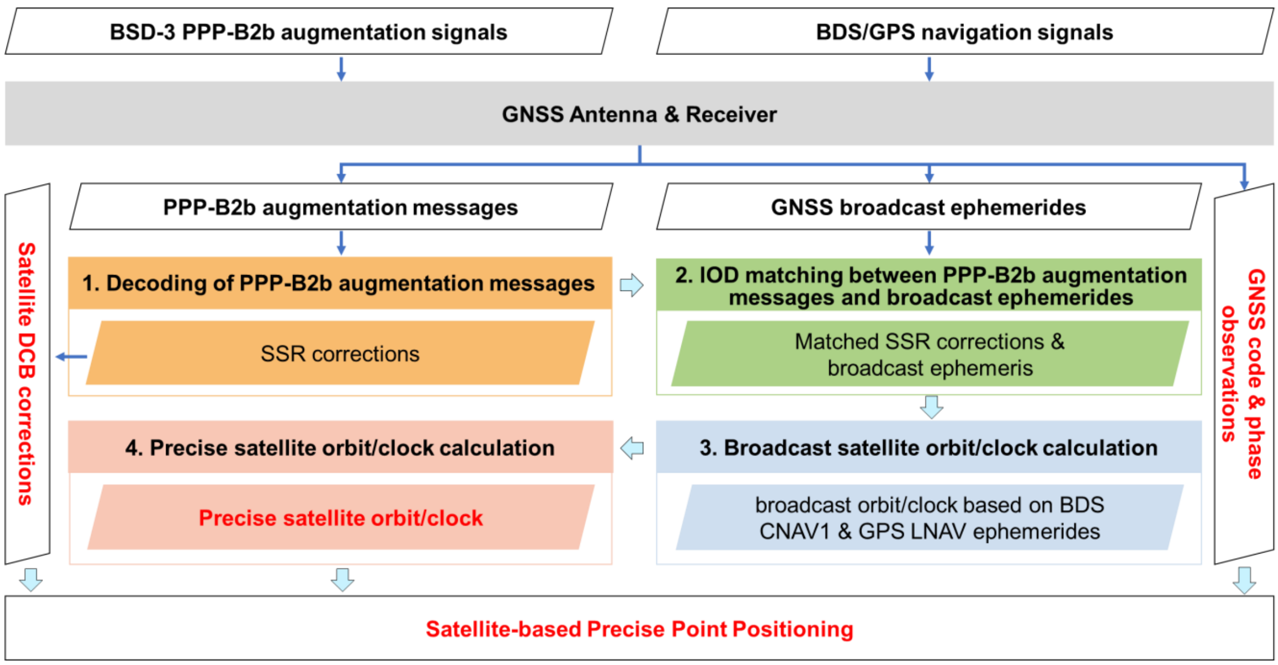

Figure 2. Procedure of satellite-based PPP based on BDS-3 PPP-B2b signals.

BDS-3 CNAV1		**GPS LNAV**	
Parameter	**Definition**	**Parameter**	**Definition**
ΔA	Semi-major axis difference at reference time	$\sqrt{A}$	Square root of the semi-major axis
$\dot{A}$	Change rate in semi-major axis	-	-
Δn_0	Mean motion difference from computed value at reference time	Δn	Mean motion difference from computed value
$\Delta \dot{n}_0$	Rate of mean motion difference from computed value at reference time	-	-

Table 2. Orbit parameter comparison between BDS-3 CNAV1 and GPS LNAV ephemerides.

Item	**BDS-3 CNAV1**	**GPS LNAV**
satellite semi-major axis (*A*)	$A_0 = A_{ref} + \Delta A$ $A_{ref} = \begin{cases} 27906100\ m\ (MEO) \\ 42162200\ m\ (IGSO/GEO) \end{cases}$ $A = A_0 + \dot{A} \cdot t_k$	$A = \left(\sqrt{A}\right)^2$
corrected mean motion (*n*)	$\Delta n_t = \Delta n_0 + 1/2 \cdot \Delta \dot{n}_0 \cdot t_k$ $n = n_0 + \Delta n_t$	$n = n_0 + \Delta n$

***: t_k is the time difference between calculation epoch and time of ephemeris (toe).**

Table 3. Orbit calculation algorithm comparison between BDS-3 CNAV1 and GPS LNAV ephemerides.

3. EXPERIMENT AND DATA DESCRIPTION

To capture BDS-3 PPP-B2b signals, a ComNav SinoGNSS K803 chip and a Harxon GPS1000 antenna were used in this study. Collected data included: PPP-B2b augmentation messages, BDS-3 B1C/B2a and GPS L1/L2 dual frequency code and phase observations, and BDS-3 CNAV1 and GPS LNAV broadcast ephemerides. More details were shown in Table 4.

Receiver chip (firmware version)	ComNav SinoGNSS K803 (601A2.p.21)
Antenna type	Harxon GPS1000
Observable	BDS-3 B1C/B2a and GPS L1/L2
Sampling interval	1 s
Elevation mask	15°
Broadcast ephemerides	BDS-3 CNAV1 and GPS LNAV
Augmentation messages	BDS-3 PPP-B2b
Location	30° 21'N, 114° 21'E, Wuhan, China.
Static experiment	DOY 168-172, 2022.
Kinematic experiment	UTC 8:00 – 14:00 on DOY 164, 2022.

Table 4. Experiment settings.

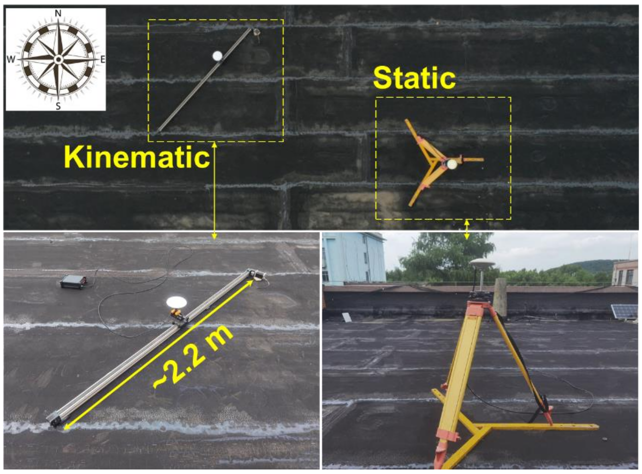

Figure 3. Experiment scenarios.

As shown in Fig.3, experiments were carried out on the roof of School of Geodesy and Geomatics in Wuhan University, China. Both static and kinematic scenarios were considered in this study. In the static scenario, the antenna was installed on a tripod for five consecutive days starting from DOY 168, 2022. In the kinematic scenario, the antenna was installed on a 2.2-m straight track. Driven by a stepper motor, the antenna moved on the track at the speed of 1 cm/s. The kinematic experiment was carried out from UTC 8:00 to 14:00 on DOY 164, 2022. After about five-hour static observation, the antenna moved on the track by five round-trips in 28 min.

4. RESULT AND ANALYSIS

With the collected dataset, this section first analyses the accuracy of precise satellite orbit/clock recovered from PPP-B2b signals. Then, the positioning performance of the BDS-3 PPP service is assessed in both static and kinematic scenarios.

4.1 Orbit accuracy and clock precision

This sub-section validates the quality of precise satellite orbit/clock based on PPP-B2b augmentation messages. GFZ rapid orbit/clock products are selected as references. Meanwhile, precise orbit/clock based on Centre National d'Etudes Spatiales (CNES) SSR corrections are also evaluated, as a comparison between the satellite-based (BDS-3 PPP-B2b) and ground-based (CNES SSR) PPP service.

Fig.4 depicts the five-day orbit error of BDS-3 (top) and GPS (bottom) during DOY 168 and 172, 2022. The left, middle and right panels represent orbit error based on broadcast ephemerides, BDS-3 PPP-B2b augmentation messages and CNES SSR corrections, respectively. After utilizing PPP-B2b augmentation messages, the BDS-3 orbit does not show much improvement over CNAV1 ephemerides. As for GPS, obvious improvement can be observed. The CNES SSR-based orbit shows the best performance as CNES corrections are determined based on globally distributed ground tracking stations. As for the three GPS orbits, it can be seen that ~1 m bias in the R direction exists in five GPS BLOCK IIIA satellites (G04/G11/G14/G18/G23) for LNAV ephemerides. After using PPP-B2b augmentation messages, biases still exist in G11, G14 and G23 during DOY 168 and 170. But this bias phenomenon is completely removed in the CNES SSR orbit.

Fig.5 shows the double-differencing (DD) clock offset with bias removed for each observation arc. Comparing with BDS-3 CNAV1 ephemerides, the BDS-3 clock performance is significantly improved by utilizing PPP-B2b augmentation messages. However, there are still several gaps in the BDS-3 clock because of CNES SSR correction missing during DOY 168 and 170. For GPS, G08 shows over 4 ns DD clock offset based on LNAV ephemerides, and this large DD clock offset is obviously corrected using the BDS-3 PPP service. CNES SSR corrections still shows the best performance over the GPS broadcast LNAV ephemerides and PPP-B2b augmentation messages.

Fig.6 summarizes the overall orbit accuracy and clock precision. Based on PPP-B2b augmentation messages, 0.551 m 3D orbit accuracies are achieved for BDS-3 MEO satellites, and 0.729 m for BDS-3 IGSO. This value for GPS is 0.554 m. The GPS orbit based on PPP-B2b augmentation messages shows 37.2% improvement over the broadcast orbit. As a comparison, the GPS orbit based on CNES SSR corrections shows 94.7% improvement, much better than that based on BDS-3 PPP-B2b augmentation messages.

For BDS-3 MEO/IGSO satellites, 0.15/0.61 ns clock precisions are achieved with PPP-B2b augmentation messages, respectively. As compared to those of BDS-3 CNAV ephemerides, the clock precisions are improved by 74.1%/33.7%, respectively. Clock precisions of GPS satellites with PPP-B2b augmentation messages are at the same level as those of GPS LNAV ephemerides, i.e., 0.29 ns versus 0.27 ns. As a comparison, clock offsets based on CNES SSR corrections achieve 0.10 ns, 0.38 ns and 0.06 ns precisions for BDS-3 MEO, BDS-3 IGSO and GPS satellites, respectively. In other words, the ground-based CNES SSR corrections outperformed the satellite-based BDS-3 PPP-B2b augmentation messages.

This contribution has been peer-reviewed. The double-blind peer-review was conducted on the basis of the full paper.
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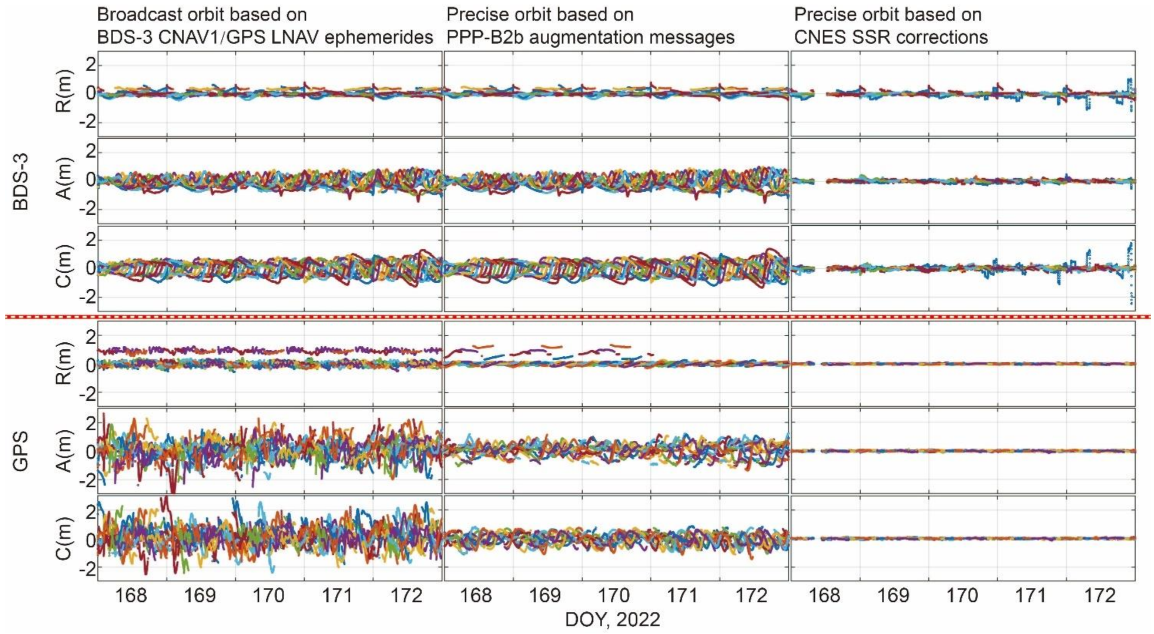

Figure 4. BDS-3 (top) and GPS (bottom) orbit errors based on broadcast ephemerides (left column), BDS-3 PPP-b2b augmentation messages (middle column) and CNES SSR corrections (right column) during DOY 168 and 172, 2022.

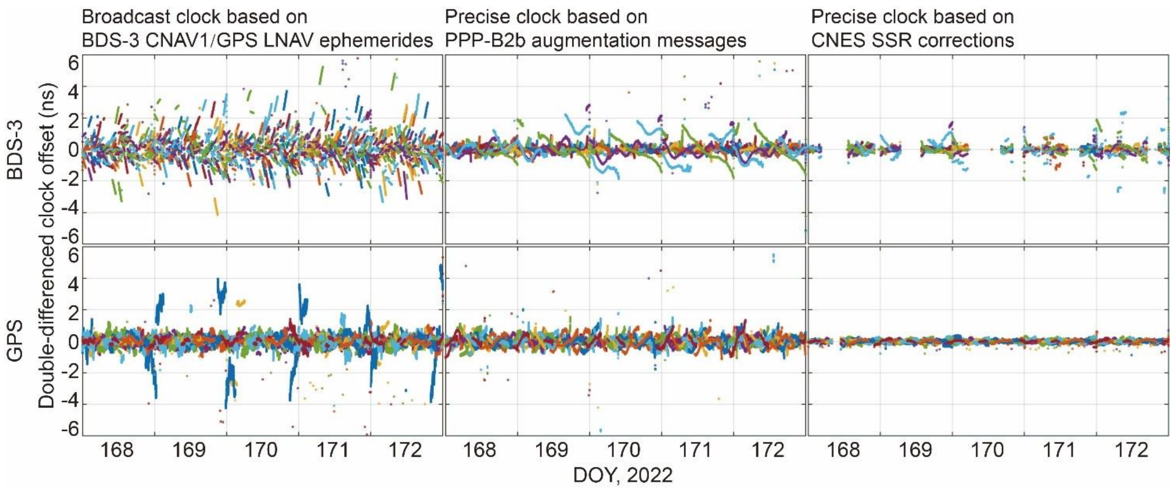

Figure 5. BDS-3/GPS DD clock offset of broadcast ephemerides, BDS-3 PPP-b2b augmentation messages and CNES SSR corrections during DOY 168 and 172, 2022.

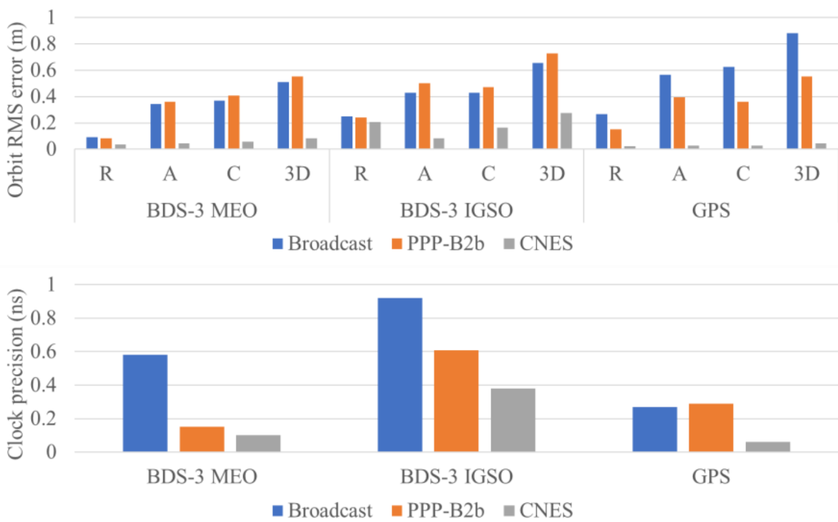

Figure 6. Overall orbit accuracy (top) and clock precision (bottom) for BDS-3 and GPS during DOY 168 and 172, 2022.

4.2 Positioning performance

This sub-section verifies the positioning performance of the BDS-3 PPP service with two experiments, i.e., the five-day static experiment and the 28-min stepper motor driven kinematic experiment. During the PPP processing, BDS-3 B1C/B2a and GPS L1/L2 code and phase ionosphere-free observations are utilized.

4.2.1 Static Experiment

BDS-3-only, GPS-only and BDS-3+GPS PPP in both static and simulated kinematic modes are implemented during DOY 168 and 172. A filter restart is triggered on UTC 00:00:00 every day. In the static mode, coordinates of the last epoch is regarded as the daily solution. Five-day daily solutions are shown in Fig. 7. The daily solution repeatability, i.e., STD of daily solutions, is used to evaluate the static PPP performance. As illustrated in Table 5, the BDS-3+GPS solution achieves the best performance with 3.9/6.9/10.3/13.0 mm repeatability in E/N/U/3D directions. These values for BDS-3-only and GPS-only are 5.3/6.7/14.2/16.6 mm and 14.4/8.1/10.0/19.4 mm, respectively. In a word, the BDS-3+GPS static PPP of BDS-3 PPP-B2b service outperformed the BDS-3 and the GPS counterpart.

System	E (mm)	N (mm)	U (mm)	3D (mm)
BDS-3	5.3	6.7	14.2	16.6
GPS	14.4	8.1	10.0	19.4
BDS-3+GPS	3.9	6.9	10.3	13.0

Table 5. Static PPP daily solution repeatability using BDS-3, GPS and BDS-3+GPS during DOY 168 and 172, 2022.

4.2.2 Simulated kinematic Experiment

Simulated kinematic PPP results are shown in Fig. 8. The reference is selected as the average of five-day BDS-3+GPS daily solutions. Table 6 summarizes the convergence time and converged accuracy. In this study, the PPP convergence is defined as: < 30 cm horizontal error and < 50 cm vertical error are achieved and hold for next 300 epochs. Similar to the static test, the BDS-3+GPS solution shows the best performance with 13.9 min convergence time and 3.42/2.16/6.65/7.81 cm converged accuracy in E/N/U/3D directions. Comparing with those of BDS-only/GPS-only solutions, the convergence time of the BDS-3+GPS solution is shortened by 89.0%/87.5%, and the converged accuracy is improved by 39.1%/51.9%, respectively.

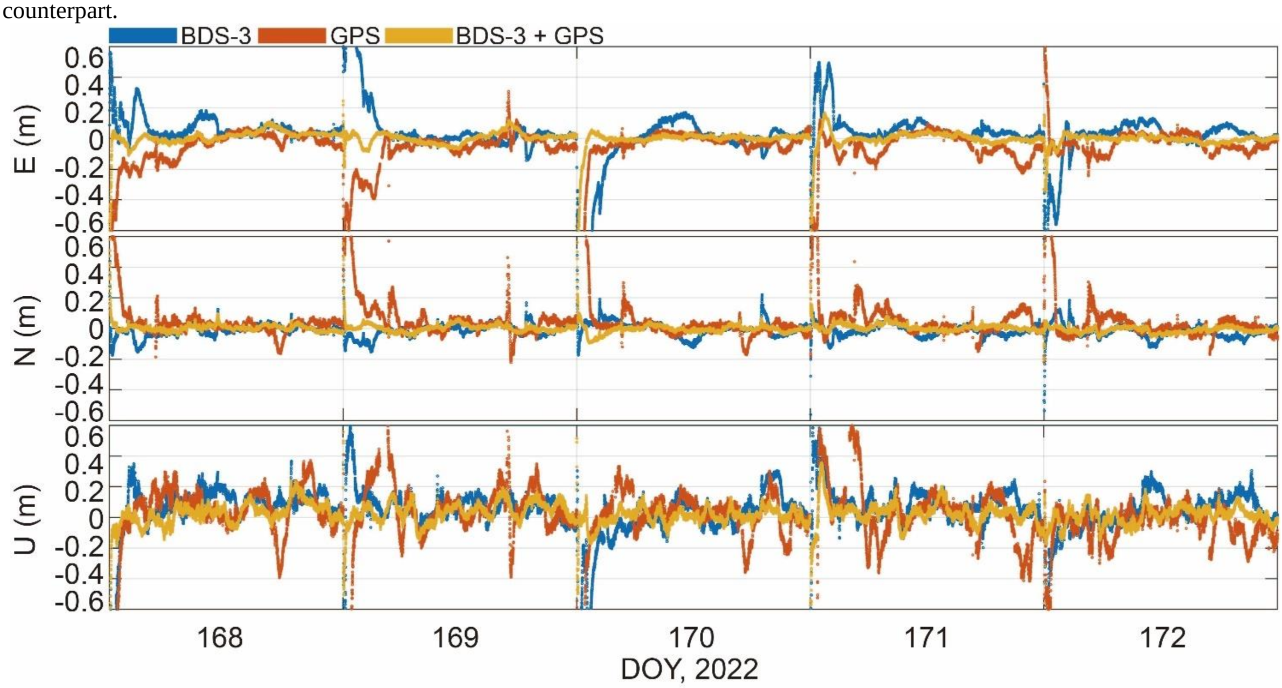

Figure 8. Positioning error of simulated kinematic PPP of BDS-3, GPS and BDS-3+GPS during DOY 168 and 172, 2022.

DOY	BDS-3					GPS					BDS-3+GPS				
	Convergence Time (min)	E (cm)	N (cm)	U (cm)	3D (cm)	Convergence Time (min)	E (cm)	N (cm)	U (cm)	3D (cm)	Convergence Time (min)	E (cm)	N (cm)	U (cm)	3D (cm)
168	48.8	8.89	3.62	12.97	16.14	73.0	8.83	4.95	13.63	16.98	10.5	3.73	1.87	7.22	8.33
169	180.0	4.18	2.99	8.43	9.88	268.8	5.38	6.33	13.41	15.77	5.8	3.72	2.26	7.72	8.86
170	158.5	7.49	4.41	10.35	13.51	77.8	4.19	4.98	11.64	13.34	23.3	3.09	2.50	4.98	6.37
171	139.5	5.68	3.27	9.91	11.88	68.8	8.63	7.85	18.91	22.22	17.5	3.70	2.10	7.86	8.94
172	102.8	6.17	4.31	10.29	12.75	69.3	6.22	5.67	9.84	12.95	12.3	2.86	2.07	5.49	6.53
Average	**125.9**	**6.48**	**3.72**	**10.39**	**12.83**	**111.5**	**6.65**	**5.96**	**13.49**	**16.25**	**13.9**	**3.42**	**2.16**	**6.65**	**7.81**

Table 6. Simulated kinematic PPP convergence time and converged positioning accuracy during DOY 168 and 172, 2022.

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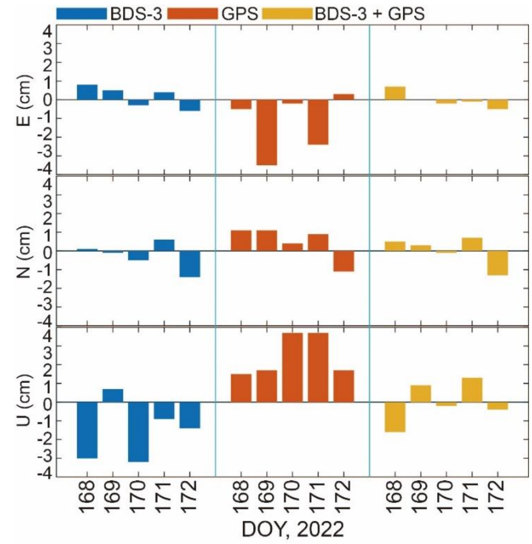

Figure 7. Five-day static PPP daily solutions using BDS-3, GPS and BDS-3+GPS during DOY 168 and 172, 2022.

4.2.3 Kinematic Experiment

The kinematic experiment starts from UTC 08:06:11 to 13:34:59 on DOY 164, 2022. The antenna stays still during 08:06:11 and 13:00:45. Then, the stepper motor starts and drives the antenna to move on the straight track for five round-trips at a speed of 1 cm/s. The stepper motor is switched off at 13:28:00. As shown in Fig. 9, the top panel depicts the number of BDS-3+GPS satellites with PPP-B2b augmentation messages. An average of 14.2 satellites are available during this experiment. The bottom panel presents the antenna displacement in E/N/U directions utilizing BDS-3 PPP-B2b augmentation messages. It is quite clear that the kinematic PPP solution is fully converged in the horizontal direction before the antenna movement.

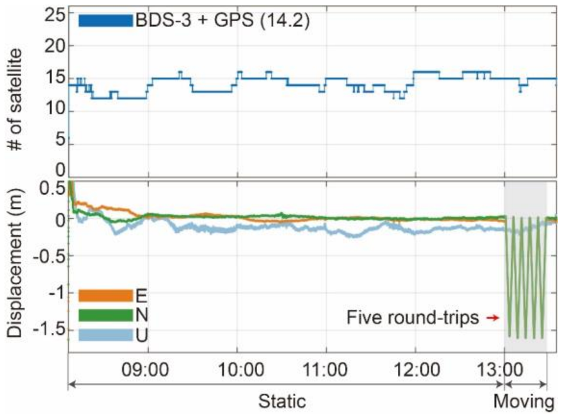

Figure 9. Number of BDS-3+GPS satellites with PPP-B2b augmentation messages (top) and antenna displacement calculated by the BDS-3 PPP service (bottom).

Since the antenna is installed on the 2.2-m straight track, the real trajectory can be considered as a line segment. In this experiment, coordinates of track's ends are determined by separate static PPP solutions, and the reference trajectory is presented as a red line shown in Fig. 10. The distance between the kinematic PPP solution and the reference trajectory is regarded as the positioning error.

The horizontal five-round-trip trajectory are also depicted in Fig. 10 with different colors. The top-left panel shows the overall trajectory, and the remaining three show zoom-in areas of the track. The distance between the first-round-trip and the reference is the largest, and the distance is gradually shortened in next four round-trips. Table 7 summarizes the positioning accuracy of each round-trip. The minimum and maximum horizontal positioning error of the first round-trip are 3.69/6.27 cm. These values decrease to 1.22/3.42 cm for the fifth round-trip. RMS errors of 2D/3D positioning result during the moving stage are 3.48/14.88 cm. To sum up, the BDS-3 PPP service can provide cm-level 2D and dm-level 3D kinematic positioning accuracy.

Round-trip	Minimum (cm)		Maximum (cm)		RMS (cm)	
	2D	3D	2D	3D	2D	3D
1st	3.69	14.82	6.27	19.26	4.81	16.80
2nd	1.80	15.67	5.41	22.10	3.82	19.00
3rd	1.73	12.19	4.12	20.13	3.07	15.73
4th	1.72	8.91	3.61	16.07	2.75	12.38
5th	1.22	4.81	3.42	12.59	2.49	8.12
Overall	**1.22**	**4.81**	**6.27**	**22.10**	**3.48**	**14.88**

Table 7. Accuracy of satellite-based kinematic PPP during the five-round-trip movement.

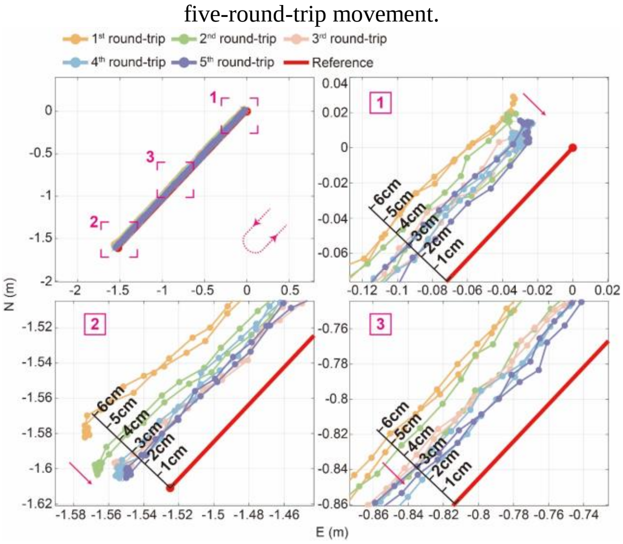

Figure 10. Antenna horizontal trajectory calculated with the BDS-3 PPP service.

5. CONCLUSIONS AND OUTLOOKS

The BDS-3 satellite-based PPP service becomes available with the PPP-B2b signal ICD released on 3 August 2020. To facilitate better understanding of BDS-3 PPP service, this paper conducts a comprehensive investigation from service usage to service performance assessment. A consecutive five-day static experiment and a 28-min stepper motor driven kinematic experiment were carried out in June 2022 in Wuhan, China. Conclusions are summarized as follows:

(1) Four steps are necessary for the utilization of BDS-3 satellite-based PPP service, i.e., decoding of PPP-B2b augmentation messages, IOD matching between PPP-B2b augmentation messages and broadcast ephemerides, broadcast satellite orbit/clock calculation based on BDS CNAV1 and GPS LNAV ephemerides, and precise orbit/clock calculation based on PPP-B2b augmentation messages.

(2) Overall orbit accuracies of BDS-3 MEO/IGSO satellites are 0.551/0.729 m, the same level as those of BDS-3 CNAV1

ephemerides. For GPS, the orbit based on PPP-B2b augmentation messages achieves 0.554 m accuracy, i.e., 37.2% improvement over GPS LNAV ephemerides. As for clock, overall precisions for BDS-3 MEO/IGSO satellites are 0.15/0.61 ns, which are improved over those of BDS-3 CNAV1 ephemerides by 74.1/33.7%. The augmented GPS clock precision is 0.29 ns, the same level as that of GPS LNAV ephemerides. It can be concluded that PPP-B2b augmentation messages mainly improve the BDS-3 clock precision and GPS orbit accuracy.

(3) The five-day static PPP results with BDS-3+GPS observations show 3.9/6.9/10.3/13.0 mm daily solution repeatability in E/N/U/3D directions. Simulated kinematic PPP results show an average of 13.9 min convergence time and 3.42/2.16/6.65/7.81 cm positioning accuracy in E/N/U/3D directions. At last, through the 28-min stepper motor driven movement test, it is verified that 3.48/14.88 cm kinematic positioning accuracy in 2D/3D directions can be achieved using the BDS-3 PPP service.

Basically, the BDS-3 PPP service shows promising performance for both static and kinematic positioning. Considering the cost-free and satellite-broadcasting characteristics, precise positioning based on PPP-B2b signals can be realized under no mobile Internet environments, such as desert and ocean regions. Therefore, more mass-market applications implementing the free BDS-3 PPP service can be developed in the near future.

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