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Principle and performance of BDSBAS and PPP-B2b of BDS-3

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Abstract

Within the framework of differential augmentation, this paper introduces the basic technical framework and performance of the BeiDou Global Navigation Satellite System (BDS-3) Satellite-Based Augmentation System (BDSBAS), including orbit products, satellite clock offset products, ionosphere and its integrity performance. The basic principle of BDS-3 Precise Point Positioning (PPP-B2b) is expounded, the similarities and differences between the PPP service provided by BDS-3 and International Global Navigation Satellite System (GNSS) Service (IGS) are discussed, and the limitations of PPP-B2b are analyzed. Since both the BDSBAS and PPP-B2b utilize a ground monitoring station network to determine the satellite orbits and clock offset corrections, and broadcast differential corrections through the three Geostationary Orbit (GEO) satellites of BDS-3, the feasibility of the co-construction of BDSBAS and PPP-B2b is analyzed, strategies for the infrastructure sharing and correction broadcasting are presented, and the influences of BDSBAS correction broadcasting strategy adjustment are evaluated. In addition, it assesses the possibility of broadcasting differential corrections through the Inclined Geosynchronous Orbit (IGSO) satellites of BDS-3, and the feasibility of augmenting satellite navigation with Low Earth Orbit (LEO) satellites.

Keywords: Satellite-based augmentation, Precise point positioning, Precise orbit, Precise clock offset, Ionospheric model

Introduction

The BeiDou Global Navigation Satellite System (BDS-3) provides four types of positioning services, i.e. Radio Determination Satellite Service (RDSS, an active positioning based on radio measurement), Standard Point Positioning (SPP), positioning based on BDS-3 Satellite-Based Augmentation System (BDSBAS) and Precise Point Positioning (PPP) through B2b signals of Geostationary Orbit (GEO) satellites (PPP-B2b) (Yang et al., 2018, 2019, 2020, 2021). The SPP of BDS-3 applies the same principle as other Global Navigation Satellite Systems (GNSSs), and its positioning accuracy is slightly better than that of Global Positioning System (GPS) because the Signal-in-Space Range Errors (SISRE) of BDS-3 is

smaller (Montenbruck et al., 2020). BDSBAS applies the same principle and standards as other Satellite-Based Augmentation Systems (SBAS), and is embedded into BeiDou Navigation Satellite System (BDS) as a component. The principle of BDS PPP is consistent with that of the International GNSS Service (IGS), but the service coverage area and service mode are different. PPP is also embedded into the BDS, and become one of the featured services.

Differential positioning is a key to GNSS positioning augmentation. Ground reference stations with high-accuracy known coordinates can be used to calculate various correction information, such as the satellite orbit errors, satellite clock offsets and atmospheric propagation errors, and then the calculated corrections are usually transmitted to user terminals. GNSS augmentation can be divided into the pseudo range and carrier phase differential augmentation. The former possesses good real-time characteristic, but relatively lower accuracy;

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the latter can achieve higher accuracy, but relatively poor timeliness for it takes a longer time for the results to converge.

The GNSS augmentation system can be divided into Ground-Based Augmentation System (GBAS) and SBAS according to the broadcasting mode of augmented information. GBAS generally broadcasts various differential corrections to users through terrestrial radio or internet, such as the Real-Time Kinematic (RTK) positioning and Local Area Augmentation System (LAAS). SBAS broadcast differential corrections through GEO satellites, which generally provide critical support for civil aviation safety. Typical SBASs include United States' "Wide Area Augmentation System" (WAAS), the European Union's "European Geostationary Navigation Overlay System" (EGNOS), Russia's "System for Differential Corrections and Monitoring" (SDCM), Japan's "Multi-Functional Transport Satellite (MTSAT) Satellite-based Augmentation System" (MSAS) and India's "GPS Aided GEO Augmentation Navigation" (GAGAN) (Shao et al., 2020).

According to the coverage of the ground monitoring (tracking) station network and the augmentation service, GNSS augmentation can be divided into wide area augmentation system and local augmentation system. The former is generally used for national-scale or regional-scale GNSS augmentation, while the latter for the high-dynamic vehicle precision approach or precision landing guidance in specific application scenarios, such as airports. RTK positioning still belongs to local augmentation even though it can provide ultra-long distance RTK service (Li et al., 2017a, b). PPP based on the IGS center products is generally regarded as wide area augmentation.

This paper focuses on the satellite-based augmentation and PPP technology and analyzes their basic principles and possible development trends.

The reliability of SBAS is a key issue for life safety. SBAS generally adopts navigation satellite signals (observations) received by continuous ground tracking stations and sends them to a ground processing center, where various corrections are calculated, such as satellite orbit corrections, clock offset corrections and ionospheric corrections. Then these corrections are broadcast to users via the GEO satellites. Considering the life safety, it is necessary to create redundancy and backup for the ground processing center, uplink station, and satellites that broadcast the corrections. In addition, integrity information is broadcast by SBAS as well.

The PPP is a generalized differential positioning method in the authors' viewpoint. PPP has been widely used in many fields since Zumberge et al. (1997) proposed the method. It generally includes a global reference station network to collect the observed GNSS data and the related service centers to calculate the satellite's precise orbits, precise clock offset, and ionospheric grid corrections which are usually broadcast to users through the internet. Some scholars regard PPP as a non-differential positioning technology. It seems that PPP can realize decimeter-, centimeter- and even millimeter-level positioning accuracy by only utilizing the precise satellite orbit, clock offset products, and corresponding precise observation models, and no need for the differential calculation from nearby reference stations. However, the corrections used in PPP rover-end including satellite orbit errors and clock offsets are indeed solved from a global reference network. It is in principle also a differential positioning but with respect to a network, instead of a single or few reference stations (Glaner & Weber 2021; Héroux & Kouba, 1995). The influences of these common errors (satellite orbit error and clock offset error) are weakened by the differential positioning model. In addition, PPP employs the carrier phase for positioning, and therefore many researches focus on the fixing of carrier-phase ambiguity parameters (Gao & Shen, 2002; Ge et al., 2008).

PPP-B2b service of China's BDS is a satellite-based service. The observations from the densified ground tracking network are collected and sent to the ground operation control center, where the precise satellite orbits and clock offsets of BDS and GPS constellations are calculated, and then uplinked to the three GEO satellites. Then the GEO satellites broadcast them through B2b signals to the users in China and surrounding areas (Yang et al., 2020, 2021).

The satellite-based augmentation services of BDS and PPP-B2b are similar, but have their own characteristics. We describe the principles and performance of BDSBAS and PPP-B2b in the following two sections, respectively. Then the possible future developments for BDSBAS and satellite-based PPP are discussed.

BDSBAS

The construction of China's SBAS, known as BDSBAS, is completed. The corresponding single frequency and dual frequency positioning performances were described and analyzed (Chen et al., 2020; Yang et al., 2021); the dual frequency integrity parameter performance of BDSBAS (Shao et al., 2020) and the ephemeris correction performance of BDSBAS in China (Jin et al., 2021) were also analyzed. Since the ionospheric correction is an important influencing factor, some scholars analyzed the ionospheric anomaly detection method of BDSBAS (Bao et al., 2019).

BDSBAS is a service component of BDS and they are constructed simultaneously. BDSBAS is composed of ground monitoring stations, a data processing center, the differential correction product uplink antenna, and

the correction broadcasting satellite system. It follows the International Civil Aviation Organization (ICAO) standards and is consistent with the principles of other international SBAS systems. BDSBAS employs the three GEO satellites of BDS-3 located at 80° E (PRN 144), 110.5° E (PRN 143) and 140° E (PRN 130), respectively, to broadcast corrections (Liu et al., 2021); the uplink system of BDS is used to inject the differential corrections of BDS and other GNSSs, calculated by the ground data processing center, into GEO satellites. Specifically, the BDSBAS-B1C signal protocol only supports GPS and GLObal NAvigation Satellite System (GLONASS), while BDSBAS-B2a signal supports BDS, GPS, Galileo Navigation Satellite System (Galileo) and GLONASS.

The time scale and reference coordinate system of BDSBAS are consistent with other existing SBAS systems, such as WAAS and EGNOS. The time system of BDSBAS is consistent with the BDS Time (BDT) $t_{\mathrm{BDT.}}$ The single frequency Service Network Time (SNT) t_{SNT} of BDSBAS can be expressed as $t_{\mathrm{SNT}} = t_{\mathrm{BDT}} + 14$, and the synchronization with GPS Time (GPST) t_{GPST} is maintained within 50 ns (CSNO., 2020). The coordinate system adopts World Geodetic System 1984 (WGS84) as required by ICAO. However, it must be noted that China's BDS adopts BeiDou Coordinate System (BDCS), which is aligned with China Geodetic Coordinate System 2000 (CGCS2000) (Yang, 2009). CGCS2000 is consistent with WGS-84 at centimeter level and the slight difference will not affect the flight safety for civil aviation users.

BDSBAS provides two augmented signals, namely BDSBAS-B1C (central frequency: 1575.42 MHz) and BDSBAS-B2a (central frequency: 1176.45 MHz). BDSBAS-B1C adopts the Binary Phase Shift Keying (BPSK(1)) modulation mode with a symbol rate of 250 bit/s, which broadcasts GPS augmentation corrections (compatible with GLONASS in the future) mainly for civil aviation single frequency users of GPS L1C/A; BDSBAS-B2a adopts the Quadrature Phase Shift Keying (QPSK(10)) modulation mode with a symbol rate of 250 bit/s, which broadcasts BDS-3/GPS augmentation corrections (compatible with Galileo and GLONASS in the future), mainly for civil aviation dual frequency users of BDS-3 B1C/B2a and GPS L1C/L1A/L5.

The data processing center is responsible for collecting the tracking data from each ground reference station and calculating the corrections of state space domain (satellite orbit corrections, satellite clock offset corrections and ionospheric error corrections) in BDSBAS. Then the master control station determines the effectiveness of the satellite signal through various integrity checks, and the modulated ranging signals with differential corrections and integrity information are broadcast to users

through the three GEO satellites of BDS-3. The level of the received BDSBAS-B1C signal at the antenna port is within the range of -161 dBW to -153 dBW, if a user can observe any GEO satellite of BDS with an elevation angle greater than or equal to 5 degrees.

In addition to broadcasting the differential corrections and integrity information of BDSBAS, the GEO satellites of BDS-3 also provide normal ranging and time transmission services through B1I and B3I signals.

The ground monitoring system of BDSBAS is temporarily composed of 27 stations (several other stations are to be built), which are basically evenly distributed throughout the territory of China.

The ionospheric model of BDSBAS adopts the ionospheric parameters determined by the ground monitoring stations, and the $5° \times 5°$ Grid Ionospheric Vertical Delay (GIVD) is obtained using the Inverse Distance Weighting (IDW) method. The user needs to calculate the ionospheric correction of the location by interpolating the values at its surrounding grid points (Bao et al., 2019; Ma et al., 2021). However, there are only about 80% grid points in China whose ionospheric delay parameters can be reliably calculated, which greatly reduce the availability and continuity of the ionospheric corrections in China's border areas due to the lack of ionospheric monitoring information in China's surrounding areas. Therefore, more monitoring stations in the surrounding areas are required for determining the ionospheric delay of BDSBAS. Like other SBASs in the United States and Japan, BDSBAS also uses Kriging fitting method to calculate the GIVD of grid points, with the aim of improving the continuity of GIVD parameters. The availability of BDSBAS GIVD can reach 99.88%, and the ionospheric integrity risk is about 0.12%.

The positioning accuracy of BDSBAS is evaluated for the different stations in the territory of China. Only the positioning accuracy of stations in Beijing, Sanya, Lhasa, Qiemo, Shanghai, Xi'an and Kunming are listed in Table 1. The data of single-frequency and dual-frequency BDSBAS from December 4 to 10, 2021, namely the Day of Year (DOY) 338–344 are used to evaluate the positioning accuracy in the horizontal and vertical components at 95% confidence level, with the sampling rate of 1 Hz.

In Table 1, HPE and VPE denote the horizontal and vertical positioning errors respectively. It can be seen from Table 1 that the BDSBAS single-frequency positioning accuracies for 7 stations are all better than 2.0 and 3.0 m in the horizontal and vertical components at the 95% confidence level, with an average of 1.48 and 2.78 m, respectively.

It can be seen from Table 2 that the averaged positioning accuracies of BDSBAS dual-frequency for 7 stations

Table 1 Single-frequency positioning accuracy of BDSBAS

Coordinate component	Beijing	Sanya	Lhasa	Qiemo	Shanghai	Xi'an	Kunming	Average
HPE (95%) (m)	1.54	1.68	1.72	1.34	1.13	1.11	1.88	1.48
VPE (95%) (m)	2.67	2.89	2.65	2.86	2.85	2.64	2.90	2.78

Table 2 Dual-frequency positioning accuracy of BDSBAS

Coordinate component	Beijing	Sanya	Lhasa	Qiemo	Shanghai	Xi'an	Kunming	Average
HPE (95%) (m)	1.28	1.67	1.35	1.84	0.84	1.06	1.12	1.31
VPE (95%) (m)	2.13	2.06	2.23	2.99	1.72	1.96	2.00	2.16

are 1.31 and 2.16 m in the horizontal and vertical components (95%), respectively. The results show that the GIVD can effectively correct the ionospheric delays in single frequency positioning, but there are residual ionospheric errors; dual-frequency users can eliminate the influence of ionosphere, and the positioning accuracy is significantly improved compared with that of single-frequency.

It must be noted that the positioning accuracy of BDS-BAS in the border areas is slightly lower than that in central areas since the ground monitoring stations are distributed in the territory of China.

The single-frequency positioning availability of BDS-BAS is greater than 99.99% in general and reaches 99.97% in some western regions. Considering the limitation of BDSBAS monitoring station distribution and the continuity and availability of ionospheric grid data, it is recommended that BDSBAS users employ the Dual Frequency Multi Constellation (DFMC) augmentation service provided by BDSBAS-B2a signal to implement precision positioning and CAT-I precision approach.

PPP-B2b

PPP-B2b embedded in BDS-3 is a featured service provided by BDS-3 GEO satellites (Yang et al., 2021). The corresponding service coverage is clearly described in the interface document. The signal design and signal format of PPP-B2b are also introduced in the relevant papers (Liu et al., 2020). Some scholars verified the service performance and the efficiency of orbit corrections and clock offset corrections (Xu et al., 2021).

The BDS-3 PPP-B2b employs dozens of high-precision continuous tracking stations (with known station coordinates and even precise time) distributed in the territory of China to track BDS satellites and obtain pseudo-code and carrier phase observations. The BeiDou operation control center calculates the precise orbits, clock offsets, differential code bias and user range accuracy index (URAI) to generate rapid ephemeris parameters, which

are sent through the uplink station to three GEO satellites and then broadcast to the users in China and its surrounding areas. Users can easily determine their locations with high accuracy by using dual-frequency BDS terminals.

The central frequency of PPP-B2b signal is 1207.14 MHz and the bandwidth is 20.46 MHz. The PPP-B2b I-component (PPP-B2b_I) signal adopts BPSK (10) modulation mode with RHCP polarization mode. When the right-hand circularly polarized antenna has 0 dBi of gain (or the linear polarized antenna has 3 dBi of gain), the minimum received power level of the PPP-B2b_I on ground is -160 dBW (CSNC, 2020).

The frame of PPP-B2b_I navigation message is concatenated together with 16 symbols of the preamble, 6 symbols of the PRN, and 6 symbols of the reserved flags to form 1000 symbols in total, and the broadcast time of each frame is 1 s after 64-ary Low-Density Parity Check (LDPC) channel coding. The reserved flags are used to identify the status of the PPP service: the "1" in the highest bit of the reserved flags means the PPP service of this satellite is unavailable; the "0" in the highest bit of the reserved flags means the PPP service of this satellite is available. According to the navigation message of PPP-B2b broadcasting strategy, it is better for users to perform PPP in a cold start mode to obtain the corrections for all satellites.

The precise orbit and clock offset corrections broadcast by GEO satellites for PPP users are mainly used to accurately correct the satellite orbit and clock offset information of the broadcast ephemeris. The differential code bias correction mainly provides the service for dual frequency or multi frequency users to improve the consistency of the code observations at different frequencies. It should be noted that the code bias broadcast by PPP-B2b is calculated by the operation control system. Some scholars found that the code bias parameters of some satellites are slightly different from the in-orbit calculation

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Table 3 Basic information of stations

Station	Agency	Receiver	Antenna
WUH2	MGEX	JAVAD TRE_3	JAVRINGANT_G5T NONE
BJF1	iGMAS	CETC-54-GMR-4016	LEIAR25.R4 LEIT
SHA1	iGMAS	Unicore UB4B0	NOV 750.R4
KUN1	iGMAS	Unicore UB4B0	NOV 750.R4

Table 4 Accuracy (root mean squares) and convergence time of BDS PPP-B2b kinematic positioning

Positioning performance		WUH2		BJF1		SHA1		KUN1	
		H	V	H	V	H	V	H	V
RMS (m)	DOY 248	0.077	0.125	0.080	0.124	0.061	0.075	0.087	0.118
	DOY 249	0.077	0.126	0.112	0.161	0.094	0.132	0.096	0.139
	DOY 250	0.077	0.136	0.116	0.132	0.093	0.122	0.107	0.111
	DOY 251	0.077	0.147	0.118	0.120	0.106	0.151	0.093	0.142
	DOY 252	0.056	0.138	0.079	0.114	0.068	0.116	0.090	0.129
	Average	0.073	0.134	0.101	0.130	0.085	0.119	0.094	0.128
Convergence time (min)		18.75		18.43		21.79		16.17	

results (Guo et al., 2015; Hu et al., 2019; Li et al., 2013, 2018).

The PPP-B2b user range accuracy index of BDS-3 mainly provides users with the priori accuracy of range observation. High precision users can use the variance component estimation or robust estimation method to estimate user range accuracy in real time and make more rational use of satellite range observation information (Yang et al., 2005).

International GNSS Monitoring and Assessment System (iGMAS) stations in Beijing (BJF1), Shanghai (SHA1) and Kunming (KUN) and a Multi-GNSS Experiment (MGEX) station in Wuhan (WUH2) are selected for the experiment. The basic information of the stations is presented in Table 3.

The data were collected from September 5 to 9, 2021 (DOY 248–252), five days in total, with a sampling interval of 30 s. The extended Kalman filter is used for parameter estimation, and the elevation cut-off angle is set as 10°. The calculation results are shown in Table 4.

Table 4 lists the Root Mean Squares (RMS) errors of PPP-B2b kinematic positioning in the horizontal (H) and vertical (V) directions after convergence. The convergence condition is that the horizontal and vertical positioning accuracies are better than 0.3 and 0.6 m, respectively, and can last for longer than 10 epochs. It should be mentioned that the accuracy of 0.3 and 0.6 m means that the horizontal and vertical component errors in the test calculation are with respect to the known coordinates of stations. In practice, however, the standard deviation of PPP positioning with a particular value may be applied for the convergence condition. It can be seen from Table 4 that the BDS-3 real-time PPP based on PPP-B2b corrections can achieve decimeter-level kinematic positioning accuracy. After convergence, the horizontal and vertical positioning accuracy is better than 0.15 and 0.2 m, respectively. The average convergence time of the selected stations is about 18 min.

The main differences between the PPP-B2b of BDS and the PPP provided by IGS are as follows.

(1) PPP-B2b provided by BDS-3 is a service embedded into GEO satellites with no need for Internet access, which is very helpful for PPP users in the areas without Internet connection or 5G network coverage, such as in ocean, desert and plateau. By contrast, IGS-PPP provides services to global users through the Internet.

(2) IGS-PPP generates GNSS precise ephemeris and ultra-fast forecast ephemeris using the selected continuous tracking stations distributed around the world and provides high-precision services to global users through the Internet. The PPP-B2b tracking stations of BDS-3 are deployed only in the territory of China, and thus the effective service of PPP-B2b is limited to China and its surrounding areas. If more observations can be obtained from the stations around the world and used in GNSS orbit and satellite clock offset calculation, the service accuracy of BDS-3 PPP-B2b will be improved.

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(3) Both the reference coordinate system and time datum of PPP-B2b are different from those of IGS-PPP. The former adopts BDCS and BDT scale, while the latter adopts the WGS 84 and GPST.

(4) The service area of BDS-3 PPP-B2b is also subject to the beam coverage of the three GEO satellites of BDS-3. PPP-B2b cannot provide services for the areas where GEO satellite signal is unavailable, no matter whether it is within the coverage of the ground tracking stations or not, because users cannot receive the precise differential corrections broadcast by GEO satellites.

(5) If the ionosphere-free combination mode is adopted to implement BDS-3 multi signal combined PPP service, the B1C/B2a combination mode is recommended for dual frequency users, and the B1C/B1I/B2a combination mode is recommended for triple frequency users (Li et al., 2020).

Possible future developments for BDSBAS and satellite-based PPP

Since BDSBAS and PPP-B2b provide similar basic products and follow similar principles, they might be possibly constructed and improved as a whole.

(1) The ground monitoring networks for BDSBAS and PPP-B2b can be co-constructed and shared. The function requirements for the two types of monitoring stations are similar, and their construction and maintenance are costly and laborious. Therefore, the ground monitoring networks should be co-constructed to realize resource sharing.

(2) BDSBAS and PPP-B2b can share the computing resource. Both need to generate precise orbit and clock offset corrections with different approaches. The former employs the pseudo-range observation or phase smoothing pseudo-range measurement to obtain orbit correction and clock offset corrections, while the latter adopts phase observations. The corresponding PPP-B2b products will achieve a slightly higher accuracy. In the authors' viewpoint, BDS-BAS can directly adopt the products with higher accuracy generated by PPP-B2b, sharing its computing resource.

(3) BDSBAS and PPP-B2b navigation message broadcasting modes can be unified on certain conditions. For PPP-B2b, the update intervals of orbit correction and clock offset correction are 48 and 6 s, respectively. For BDSBAS, the update interval is 120 s for satellite orbit correction (dx/dy/dz) and 300 s for the grid ionosphere parameter. The update period for the fast correction parameters (mainly the combined corrections of orbit and clock offset after deducting broadcast ephemeris and long-term corrections, together with corresponding fast corrections and the integrity parameters) is 6 s. If the update time intervals for the orbit corrections are unified to 48 s and for satellite clock offset corrections are set to 6 s, both requirements of PPP-B2b and BDSBAS can be met. In this case, the fast correction parameter tends to be very small for BDS-BAS compared to its accuracy, which can be set to zero and omitted.

It must be noted that the message data rate of BDS-BAS is different from that of PPP-B2b, i.e., 250 bit/s for BDSBAS and 500 bit/s for PPP-B2b. PPP-B2b broadcasts more messages with shorter interval, and the rate is to be upgraded to 1000 bit/s or 2000 bit/s in the future. In order to share messages broadcast by them, the BDSBAS must be backward compatible, which means that the BDSBAS user terminal may need to be changed appropriately to improve the positioning accuracy. If the SBAS user does not change the reception mode, the message of PPP-B2b and BDSBAS can still be broadcast separately.

It should be noted that SBAS needs to broadcast the integrity information, which has not yet been considered in most PPP services. However, the integrity information and early warning of abnormal information can also be helpful for regular navigation and positioning users because the robustness of data processing can be improved by selecting observations with reference to the early warning information.

(4) In addition to functioning as normal navigation, positioning and timing satellites, the three BDS-3 GEO satellites broadcast the differential corrections of BDSBAS and PPP-B2b and provide short message communication service and RDSS. If the two types of correction products of BDSBAS and PPP-B2b are combined and the resulting product is uplinked to GEO satellites as a whole, then the pressure on uplink and broadcast channel can be reduced and the broadcasting platform and the uplink and downlink channel can be shared.

(5) Globally, most SBASs use GEO satellites to broadcast differential corrections, and users in northern hemisphere are subject to the "south wall effect" (Yang et al., 2020), which means that the GEO signals can be easily blocked by the obstacles in its south. In order to improve the availability of satellite-based augmentation differential corrections, IGSO satellites can also be used to jointly broadcast the corrections of BDSBAS and PPP-B2b. The expected service coverage after the participation
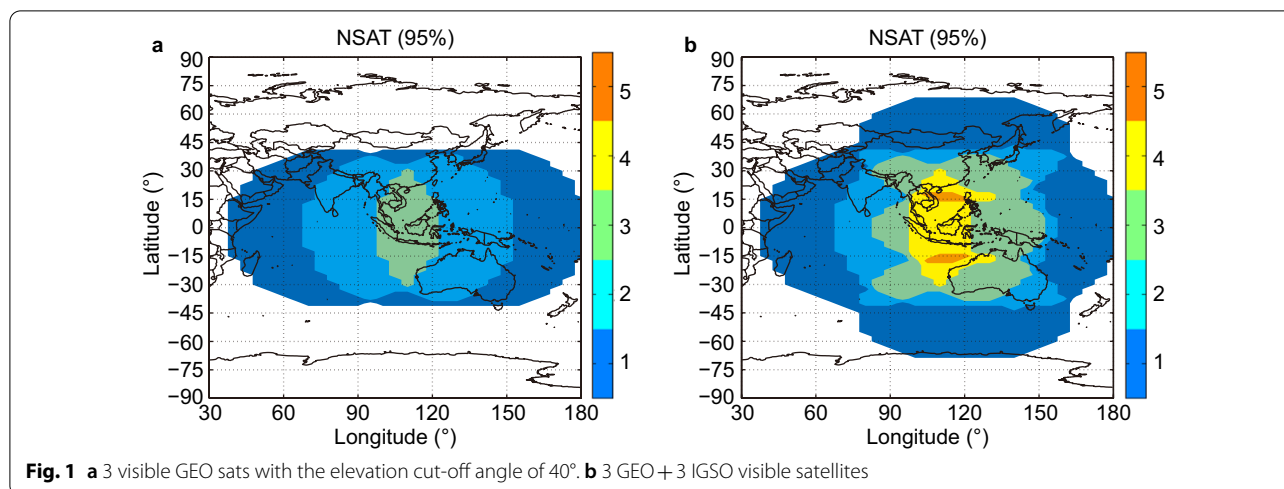
Fig. 1 **a** 3 visible GEO sats with the elevation cut-off angle of 40°. **b** 3 GEO + 3 IGSO visible satellites

Table 5 Convergence time of PPP-B2b + LEO

Stations	Convergence time of 10 cm accuracy (s)	Convergence time of 100 cm accuracy (s)
Beijing	44	7
Wuhan	59	17
Kunming	49	19
Shanghai	68	7

of the IGSO satellites is shown in Fig. 1. With the increase of the Number of visible SATellites (NSAT) with a probability of 95%, the service coverage will be obviously expanded, and the "south wall effect" of BDSBAS and PPP-B2b services for users in the Asia-Pacific region will disappear.

(6) The development of LEO constellation for augmentation will also improve the service mode and performance of SBAS and satellite-based PPP. On one hand, LEO satellites can broadcast satellite-based augmentation corrections; on the other hand, LEO satellites and BDS-3 satellites can form a hybrid constellation to broadcast normal navigation and positioning signals, which will significantly improve the geometric strength of the integrated constellation, and then improve the orbit precision of BDS-3 satellites and the measurement accuracy of satellite clock offset. The participation of LEO constellation in providing PPP-B2b service can effectively improve the convergence speed of PPP-B2b (Li et al., 2022). Assuming that 120 LEO satellites at an altitude of 975 km with an orbital inclination of 55° are evenly distributed on 12 orbital planes and participate in PPP service together with PPP-B2b, the required convergence time corresponding

to the positioning accuracies of 10 and 100 cm are shown in Table 5.

Obviously, with the support of LEO satellites, the "south wall effect" can be eliminated and the 1 and 0.1 m positioning accuracy can be achieved within 20 s and around 1 min, respectively.

(7) With the wide application of satellite-based augmentation and PPP, most ground-based augmentation services will gradually lose their significance.

Conclusions

BDSBAS and PPP-B2b are two types of embedded satellite-based augmentation services of BDS-3. They are important components and featured services of BDS-3. The single frequency positioning performance of BDSBAS can meet the CAT I precision approach requirements of ICAO, with the horizontal and vertical positioning accuracies better than 2.1 and 3.5 m, respectively. The positioning accuracy in China's surrounding areas is slightly lower, due to the fact that the ground monitoring stations are only deployed in the territory of China and the continuity of the ionospheric monitoring is relatively poor. The latest service performance of PPP-B2b is as follows: the horizontal and vertical positioning accuracies are approximately 0.15 and 0.2 m; if the positioning accuracies are required to be better than 0.3 and 0.6 m in the horizontal and vertical components, the convergence time is within 20 min in general.

Both BDSBAS and PPP-B2b need a ground monitoring station network, computing center and differential correction broadcasting platform. Therefore, we can formulate an integrated plan to coordinate and optimize

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the construction of them and employ the same ground monitoring station network and computing center. The precise orbit and clock offset of PPP-B2b can be used for the orbit correction and satellite clock offset correction of BDSBAS, the broadcasting frequency is also based on that of PPP-B2b, and the integrity information can be provided to both BDSBAS and PPP-B2b users.

If IGSO satellite is also added to BDSBAS and PPP-B2b augmentation signal broadcast, the "south wall effect" will be reduced and the service availability will be improved. If LEO satellite augmentation is adopted, not only the "south wall effect" can be eliminated, but also the positioning accuracy will be significantly improved, and the convergence time will be shortened.

Authors' contributions
YY proposed the idea and drafted the article; QD provided the results of BDS-BAS; WG provided the results of LEO satellites joint with PPP-B2b; JL calculated the coverage contribution of IGSO satellites; YX provided the new calculation results of PPP-B2b in the territory of China; BS assisted in text-proofing and manuscript revision. All the authors read and approved the final manuscript.

Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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