Key Technical Characteristics and Performance of BeiDou Navigation Augmentation System Based on LEO Constellation

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Abstract. This paper studied a BeiDou navigation augmentation system architecture based on the LEO constellation and analyzed the key factors that affected the performance of the system. The paper also carried out four aspects of the system design and the performance quantification analysis, such as establishing and maintaining Spatio-temporal reference, constellation design, signal design, and user positioning calculation. The paper's research results can also be used to reference the design and construction of the new generation of the PNT system.

Keywords: BeiDou Navigation System (BDS) · Positioning, Navigation, and Timing (PNT) Architecture · Low Earth Orbit (LEO) Constellation · Navigation Augmentation

1 Introduction

The BDS-3 system was completed constructed and put into service on July 31, 2020. The space segment of the system consists of 30 satellites (24 MEO, 3 GEO and 3 IGSO). The global positioning accuracy less than 10 m, the velocity measurement accuracy less than 0.2 m per second, the timing accuracy is better than 20 ns, the service availability is better than 99%, and the performance in the Asia-Pacific region is much better [1].

However, the navigation system that only relies on the MEO/GEO/IGSO satellites has been faced with significant bottlenecks in improving accuracy, security and coverage. Therefore, it is necessary to look for some new technical approaches.

Since 2008, the concept of comprehensive PNT system [2, 3] has become a new research hot spot, which refers to the systematic development of the corresponding augmentation, supplement and backup mean based on the idea of the system and the method of SoS (System of System), with the MEO/GEO/IGSO satellite constellation as the core, to realize complementary advantages.

According to the latest PNT architecture, there are some limitations to the current augmentation methods. For example, the Ground Augmentation System (GAS) has limited coverage and is difficult to be constructed and maintained in remote areas and offshore. The landing level of the space-based augmented signal based on medium and high-orbit satellites is similar to that of current satellite navigation signals. The

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continuous improvement of signal power is limited by satellite energy consumption and weight resources constraints. The LEO satellites, with the characteristics of higher landing level, information rate and ground speed (GS), are more than 20 times lower from the ground than MEO/GEO/IGSO satellites. Therefore, LEO satellites are very suitable to complement with the MEO/GEO/IGSO satellites, and have been paid much more attention [4].

Based on summarizing the System architecture of the BS Joint LEO Constellation, and aiming further to improve the high accuracy and fast convergence service capability, this paper will study the key technical systems and solutions of the LEO augmentation system, and give the results of performance analysis and evaluation, to provide a reference for the development of the next generation of BDS.

2 System Architecture

The BeiDou Satellite Navigation Augmentation System based on the LEO constellation establishes Spatio-temporal reference of the BDS and augments and its performance by constructing reasonable LEO constellation and broadcasting augmented navigation signals and message information. The system architecture is shown in Fig. 1.

2.1 Space Segment

The space segment consists of the LEO constellation and the BDS constellation, which relies on the completed global BDS-3 System. The LEO constellation can depend on several domestic, commercial constellations, some of which can be equipped with navigation augmentation functions and load some high-accuracy GNSS receivers to get BDS downstream navigation signals. Meanwhile, they can also generate the Spatio-temporal reference handed to the GNSS system, determine the orbit of LEO satellites, and calculate the time synchronization data under the ground system's corresponding supports, as well as generate and broadcast the augmented navigation information, to realize the BDS navigation augmentation service.

2.2 Ground Segment

The ground segment consists of the BDS ground segment and the LEO ground segment. The former is based on the existing the BDS ground monitoring station, the measurement and control station, as well as the operation and control station, which can continuously monitor BeiDou navigation signals and provide real-time observation data. The latter consists of the LEO constellation master control centre, the uplink station, as well as the measuarement and control station. As an operational control centre of the whole system, the LEO constellation management centre can collect all the raw observations of the LEO navigation signals and BDS navigation signals to carry out system time synchronization processing and satellite clock bias prediction, satellite orbit processing, and broadcast ephemeris forecasting. Meanwhile, the centre is also responsible for task planning and scheduling, operation management and control of the whole system. The monitoring station is equipped with a monitoring receiver for LEO augmentation service to continuously monitor the augmented signals of LEO navigation and provide real-time observation data. According to the plan, the uplink station receives the command from the centre and uploads various parameters to the visible LEO satellite. Measurement and control station is used for telemetry and remote control mission management of LEO constellation.

2.3 User Segment

The user segment is mainly configured with various user terminals, which can obtain the position and time service information by calculating and processing the signals received by the BeiDou and LEO satellites.

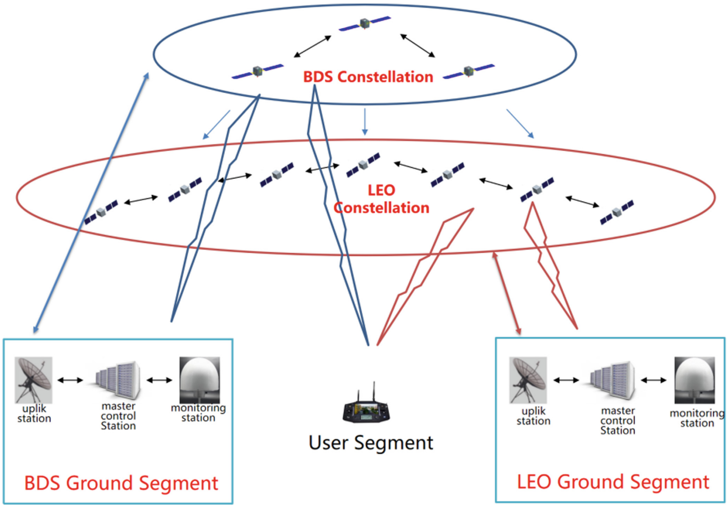

Fig. 1. The architecture of the BeiDou navigation augmentation system based on the LEO constellation

3 Key Technical System and Performance Analysis

To realize the navigation augmentation with LEO constellations, the critical technical problems restricting its service performance, are necessary to be solved through the practical technical system design, to obtain user satisfaction. The key elements involve many aspects, and the first is to solve the establishment and maintenance of the Spatio-temporal reference of the LEO satellite, which is the fundamental basis of realizing the service capability of the LEO satellite. The second is to construct a reasonable constellation architecture to easily obtain excellent coverage ability and achieve high accuracy geometric characteristics. The third is to design easy-to-use LEO satellite navigation signals provides users with the physical links of accurate ranging and data transmission. The fourth is to create a simple and efficient positioning solution algorithm, which is convenient for the user to obtain the required accurate and reliable position and time information through the comprehensive processing of observation data.

3.1 Construction and Maintenance of LEO Spatio-Temporal Reference

The constraints of satellites themselves limit the construction and maintenance of LEO Spatio-temporal reference, so we cannot copy the scheme of MEO/GEO/IGSO satellites. In terms of the temporal reference, due to the limitation of the weight, volume, energy consumption, cost and other factors, it is challenging to configure high-performance atomic clocks to maintain the time system of LEO satellites. In terms of spatio reference, the multi-orbit perturbation force received by LEO satellites are higher than that received by MEO/GEO/IGSO satellites, so it is necessary to use a better way and more precise model parameters to determine the high-accuracy orbit. To solve the above problems, the paper uses the BeiDou satellite system as the Spatio-temporal reference of the LEO satellite. The high-precision space-borne BeiDou receiver can be mounted on the LEO satellite to receive data, to construct the Spatio-temporal reference of the LEO satellite matching the BeiDou Navigation Satellite System.

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3.1.1 Orbit Determination and Forecast by Autonomous Calculation on the Single LEO Satellite

It is tough to determine and forecast the precise orbit of LEO satellites, because the atmospheric resistance, the Earth non-spherical gravity and the general relativity effect of LEO satellites are stronger than those of MEO and IGSO satellites. Therefore, the perturbed motion of LEO satellites is more complex, and its parameter requirements of the orbit determination model are higher as well. Usually, there are two kinds of methodologies to determine the orbit of LEO satellites. The first type of the approaches is on the bias of the ground processing. We can uniformly observe MEO/GEO/IGSO satellites based on the ground segment, and make precise orbit determination and prediction of LEO satellites by GNSS measurement data transmitted from LEO satellites. This method requires multiple transmissions of data between the satellite and the ground. However, when the constellation scale is larger, the control is more complicated, and the requirement for link stability is higher. The second type of approaches is based on autonomous satellite processing. The MEO/GEO/IGSO satellites are observed directly from the LEO satellites to receive GNSS precise orbit and clock error. Then the orbit is determined and forecast by way of autonomous calculation on the satellite. This method relatively increases the requirements of the on-board processing capacity of the satellite, but it is less dependent on the ground segment and more robust overall. Considering the constraints of space-borne hardware resources and processing capacity, we can use simplified dynamics to process the data from the space-borne receiver and carry out real-time computation on the satellite.

The in-orbit observation data of the first test satellite of Hongyan are used to simulate in-orbit processing and verification on the ground, and the inner coincidence is compared shown in Fig. 2. It is shown that the along, corss and radial RMS values of the precision orbit determination are 1.7 cm, 1.1 cm and 2.2 cm, respectively, and the orbital URE is 2.3 cm, which met the requirements of precision orbit determination.

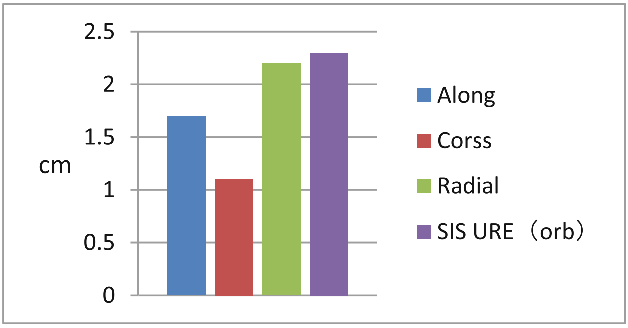

Fig. 2. The precision orbit determination results of the first test satellite of Hongyan

3.1.2 Establishing the High-Precision Temporal Reference Based on the Space-Borne Crystal Oscillator

Time and frequency is the core of the satellite navigation system. To maintain high accuracy and high stability of the time and frequency on the satellite, the space-borne atomic clocks such as hydrogen clock, rubidium clock and cesium clock are widely used on MEO/GEO/IGSO satellites of BDS, GPS and other satellite systems. Meanwhile, considering the requirements of life and reliability, 3 to 4 clocks are generally configured. Besides, the higher requirements of the weight, power consumption, cost of the satellite are put forward. Compared to MEO/GEO/IGSO satellites, the LEO satellite has far less carrying capacity but far more quantity. If the LEO satellite also adopts the configuration scheme of space-borne atomic clocks, the cost will be unacceptable. Therefore, the available alternative scheme must be adopted. The options include CSAC (Chip Scale Atomic Clock), small rubidium clock, and high-stability crystal oscillators. Their primary performance is shown in the following table. The low stability performance of the CSAC cannot meet the requirement of millimetre carrier phase measurement. The volume, weight, and power consumption of the small rubidium clock are several times higher than those of other schemes, which indicates that the satellite platform requires more resources and the short-stability performance is difficult to meet the requirements. Although the high stability crystal oscillator can achieve excellent short-term stability index, its disadvantage is that maintaining stability in the long term is weak.

Therefore, the method of handing high-stability crystal oscillators by GNSS signals can achieve better short-stability and long-stability indexes, which can effectively reproduce the performance of space-borne atomic clock on MEO/GEO/IGSO satellites on LEO satellites at low cost, and meet the requirements of LEO satellites for time-frequency signal generation and maintenance.

Table 1. Alternative Scheme for Space-borne Clocks

No.	Indicators		CSAC (MEMS)	CSAC (traditional)	Small rubidium clock	High-stability Crystal Oscillators
1	Output frequency		10 MHz	10 MHz	10 MHz	10 MHz
2	Stability	1 s	$\leq 1 \times 10^{-10}$	$\leq 8 \times 10^{-11}$	$\leq 3 \times 10^{-12}$	$\leq 3 \times 10^{-13}$
		10s	$\leq 3 \times 10^{-11}$	$\leq 3 \times 10^{-11}$	$\leq 1 \times 10^{-12}$	$\leq 5 \times 10^{-13}$
		100s	$\leq 1 \times 10^{-11}$	$\leq 8 \times 10^{-12}$	$\leq 2 \times 10^{-13}$	$\leq 2 \times 10^{-12}$
		1000s	$\leq 5 \times 10^{-12}$	$\leq 4 \times 10^{-12}$	$\leq 1 \times 10^{-13}$	$\leq 3 \times 10^{-12}$
		10000s	$\leq 3 \times 10^{-12}$	$\leq 4 \times 10^{-12}$	$\leq 1 \times 10^{-13}$	$\leq 1 \times 10^{-11}$
3	Drifting Rate Per Day		$\leq 5 \times 10^{-12}$	$\leq 2 \times 10^{-11}$	$\leq 1 \times 10^{-12}$	$\leq 1 \times 10^{-10}$
4	Power Consumption		≤220 mW	≤ 2 W	≤30 W	≤5 W
5	Weight		≤60 g	≤250 g	≤1800 g	≤650 g
6	Volume		$\leq$ 21 cm^3	$\leq$160 cm^3	$\leq$ 2100 cm^3	$\leq$320 cm^3

3.2 LEO Satellite Navigation Augmentation Constellation

LEO satellite constellation is a crucial element to improve navigation performance. Its goal is to obtain excellent coverage performance and observation geometry and consider the many indicators such as system cost, fault tolerance, and stability. In essence, it is a multi-objective and multi-constraint optimization problem, which means to find the constellation configuration parameters satisfying the target performance under various constraints.

As for the parameters design of LEO constellations, one type is the orbit with a small and medium inclination of 40–60°. Such orbital satellites have better performance in multi-repetition coverage of densely populated areas in middle and low latitudes, so they are suitable for the core constellation of navigation augmentation. The other type is the near-polar orbit with an inclination near to 90°, which is mainly used in the LEO communication system to meet the requirements of the single coverage required by communication and is suitable for the mixed and supplement constellation of navigation augmentation to improve the coverage performance in high latitudes. The other is the near-polar orbit with an inclination of more than 80°, and satellites in this kind of orbit are often used in LEO communication systems. It is mainly used to meet single coverage requirements for communication and is suitable for improving the coverage performance in high latitudes as a complement constellation for navigation augmentation. The above two types of orbital features and coverage effects are different so that their function is also different. Therefore, the combination of the above two options is a more balanced solution for navigation augmentation. Based on this consideration, to facilitate the analysis and calculation in the following paper and without generality loss, the orbital altitude is set as 1000 km. The available constellation configuration scheme is shown in the table below. Based on this consideration, to facilitate the analysis and calculation in the following paper with the generality, the orbital altitude is set as 1000 km. The available constellation configuration scheme is shown in Table 2.

Table 2. Main parameters of LEO constellation

No.	Constellation	Orbital altitude	Orbital inclination	Quantity of the satellites	Orbital configuration
1	Core (L150)	1000 km	30°	30	Walker 30/3/1
		1000 km	55°	90	Walker 90/9/1
		1000 km	86°	30	3 orbital planes; 10 evenly distributed satellites per orbital plane
2	Communication + Navigation (L72)	1000 km	88°	72	6 orbital planes; 12 evenly distributed satellites per orbital plane
3	Communication + Navigation (L144)	1000 km	88°	144	12 orbital planes; 12 evenly distributed satellites per orbital plane

3.3 Augmented Navigation Signal System

The navigation signals of major navigation satellite systems in the world are the same as those of BeiDou Navigation Satellite System, whose frequencies are all selected in the L-band (as shown in Fig. 16). The adoption of some similar frequency domain parameters,such as frequency point, modulation mode, and the bandwidth, on the one hand, can solve the problem of the lack of frequency resources, on the other hand, it can reduce the burden of providing reference frequency for different centre frequency in the receiver, simplify the design and manufacture of receiver for the multi-system satellite navigation system, and reduce the power consumption, cost and weight. In the aspect of signal interoperation, the same or similar carrier frequency has a significant impact on the development cost and technical complexity of navigation receiver. The selection of other characteristics of navigation signals, such as modulation mode, signal structure, spread spectrum code, only needs to adjust the receiver baseband processing software, which has a relatively small impact. Based on the above considerations, the L frequency band is selected as the working frequency band of LEO navigation augmented signal. The signal adopts the modulation mode similar to BeiDou, and the same family of spread spectrum code parameters. Simultaneously, considering the general needs of dual-frequency applications, dual-frequency signals are used to augment navigation on LEO satellites.

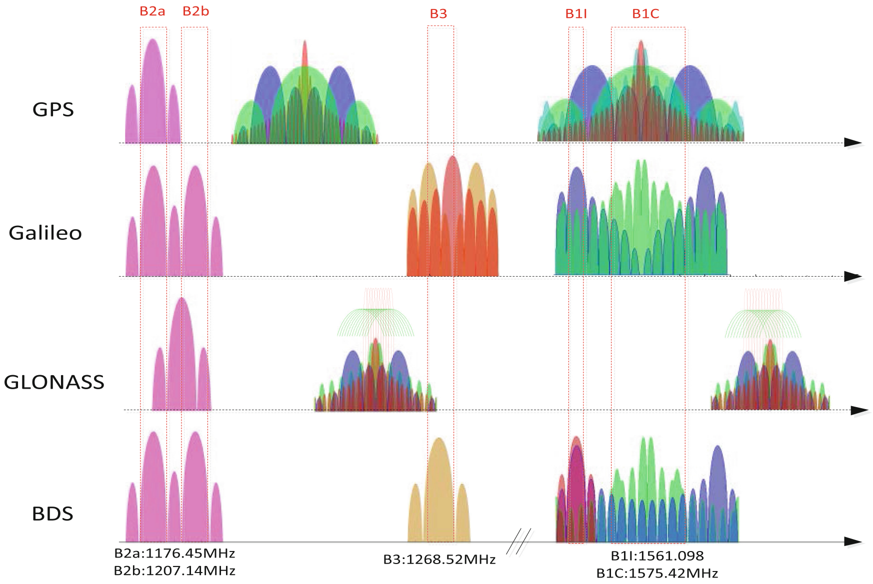

Fig. 3. Signal spectrum diagram of Four GNSS

3.4 The Precise Positioning Method Based on the Mixed Constellation Augmentation

3.4.1 Analysis of LEO Satellites Acceleration Precise Positioning Convergence

The fast motion of LEO satellites can effectively improve the geometric characteristics of the positioning equation of GNSS medium and high-orbit satellites.

Assuming that the user's clock is completely synchronized with the system and all kinds of errors are corrected, as well as, and the ambiguity of the initial carrier phase observation value has been accurately determined using the pseudo-distance reference, the position of the receiver can be determined with only three satellites. The simplified positioning equation is as follows:

$$\begin{bmatrix} \frac{\partial f}{\partial X_1} & \frac{\partial f}{\partial Y_1} & \frac{\partial f}{\partial Z_1} \\ \frac{\partial f}{\partial X_2} & \frac{\partial f}{\partial Y_2} & \frac{\partial f}{\partial Z_2} \\ \frac{\partial f}{\partial X_3} & \frac{\partial f}{\partial Y_3} & \frac{\partial f}{\partial Z_3} \end{bmatrix} \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} = \begin{bmatrix} \Delta L_1 \\ \Delta L_2 \\ \Delta L_3 \end{bmatrix} \tag{1}$$

In the above equation, each row of the coefficient matrix represents the unit vector of the satellite direction of the receiver, the unknown variable is the change of the position of the receiver, and the right side of the equation is the change of the observed value on the unit vector of the satellite of the receiver. The above equation is expressed in matrix form as follows:

$$\mathbf{Gx} = \mathbf{b} \tag{2}$$

According to matrix theory, the condition number of matrix of an invertible square matrix $\mathbf{G}$ can be defined as $cond(\mathbf{G}) = ||\mathbf{G}||||\mathbf{G}^{-1}||$, where $\|\bullet\|$ represents the matrix norm. When the solutions $\mathbf{x}$, $\delta\mathbf{x}$ of the equation satisfy $\mathbf{Gx} = \mathbf{b}$, $\mathbf{G}(\mathbf{x} + \delta\mathbf{x}) = \mathbf{b} + \delta\mathbf{b}$, the following equation is available:

$$\frac{1}{cond(\mathbf{G})}\frac{\|\delta\mathbf{b}\|}{\|\mathbf{b}\|} \le \frac{\|\delta\mathbf{x}\|}{\|\mathbf{x}\|} \le cond(\mathbf{G})\frac{\|\delta\mathbf{b}\|}{\|\mathbf{b}\|} \tag{3}$$

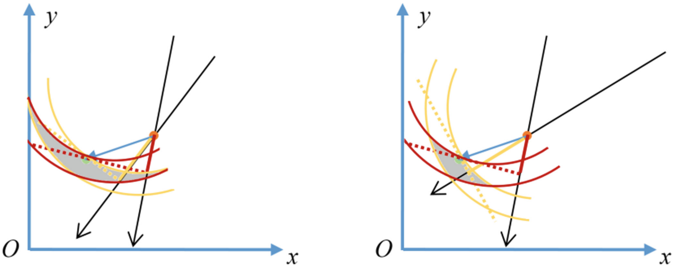

Fig. 4. Illustrating the effect of the addition of LEO satellites on the solution based on the two-dimensional diagram

When the relative error $\|\delta\mathbf{b}\|/\|\mathbf{b}\|$ of $\mathbf{b}$ is fixed, the smaller the condition number $cond(\mathbf{G})$, the larger the lower boundary and the smaller the upper boundary of the relative error of the solution. It shows that the smaller the condition number is, the more controllable the error of the solution is, the higher the accuracy of the solution is, and the faster the convergence speed is. As shown in the figure above, in the simplified two-dimensional space, the rapidly changing geometric characteristics of LEO satellites can effectively reduce the conditions number, improve the accuracy of the solution, and significantly improve the convergence rate.

3.4.2 Precision Positioning Simulation Analysis on MEO/GEO/IGSO Constellations

Based on BDS-3, the mixed constellation scenarios are respectively constructed, as shown in Fig. 5, BDS + 150LEO, BDS + 150LEO + 72LEO and BDS + 150LEO + 72LEO + 144LEO. Moreover, the observation data of different latitude stations are simulated, and the precision positioning simulation based on hybrid constellation augmentation is verified.

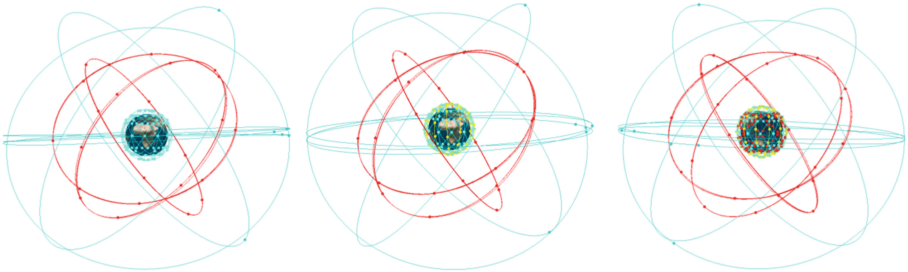

Fig. 5. Schematic diagram of the mixed constellation architecture

Select three stations at high, middle and low latitudes respectively, select Beidou B1C and B2A dual frequency signals, set the convergence threshold as 0.1M, cut-off altitude angle as 15° and count the convergence time under the above three scenarios. It can be seen that when the elevation mask is 15°, the addition of LEO constellation will significantly improve the convergence speed regardless of the latitude of the station distribution. Moreover, for the same station, the convergence is faster when more LEO satellites are introduced. As shown in Fig. 6, for the three stations at low latitude, middle latitude and high latitude, the convergence time can be shortened from 17 min 30 s, 19 min 35 s and 24 min 55 s to 0 min 40 s, 34 s and 45 s with only BDS, respectively, and the degree of shortening is 96.19%, 97.16% and 96.99%, respectively. As shown in Fig. 6, when 150 LEO satellites are added, compared with the situation when only BeiDou satellites are included, for the three stations at low, medium and high latitudes, the convergence time is shortened from 17 min 30 s, 19 min 35 s, 24 min 55 s to 0 min 40 s, 34 s and 45 s respectively, and the degree of shortening is 96.19%, 97.16% and 96.99%, respectively. With the addition of the mixed constellation, the convergence rate is higher and higher, and the convergence time is reduced to 25s, 22s and 21s respectively when 150 + 72 + 144 LEO satellites are added.

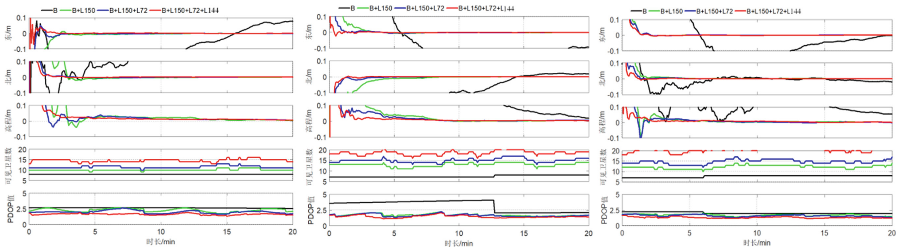

Fig. 6. Comparison of convergence time at high, medium and low-latitude stations

Table 3. Convergence time at high, medium, low latitude stations (elevation mask = 15°)

LEO constellation	High-latitude station		Medium-latitude stations		Low-latitude stations	
	Convergence time	Degree of reduction	Convergence time	Degree of reduction	Convergence time	Degree of reduction
0	24′55”	0%	19′35”	0%	17′30”	0%
L150	00′45”	96.99%	00′34’	97.10%	00′40”	96.19%
L150 + L72	00′34”	24.44%	00′28’	17.65%	00′33’	17.50%
L150 + L72 + L144	00′21”	38.24%	00′22”	21.43%	00′25”	24.24%

4 Conclusion

According to the establishment and maintenance of Spatio-temporal reference, constellation design, signal design and user positioning calculation, the paper carries out the system design and quantitative analysis of precision positioning performance based on the hybrid constellation. The simulation results show that the convergence time can be shortened by more than 96% by adding LEO augmentation core constellation (L150) to the BeiDou system. On this basis, the convergence time can be further shortened by 17% and 21% by adding LEO augmentation mixed constellations (L72 and L144). The research results of the paper can provide a reference for the design and construction of a new generation of PNT system.

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