Evaluation of BDS-2/BDS-3 Precise Point Positioning Performance in Polar Region

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Abstract. In order to increase the understanding of the positioning performance of BDS in the polar regions, this paper analyzes PPP (precise point positioning) performance under five different combinations which include BDS-3(B1IB3I), BDS(B1CB2a), BDS(B1IB3I), BDS(B1CB2a+B1CB3I) and GPS(L1L2) using the observation data of 15 IGS (International GNSS Service) stations around the world for 30 days. The results show that the accuracy of the static PPP in polar regions in the three directions of NEU is 1.1 cm, 0.7 cm, and 1.7 cm, and the kinematic PPP accuracy is 10 cm, 9 cm, and 20 cm. The time for static PPP in the polar region to converge to within 10 cm in the three directions of NEU is less than 15 min, 11 min, and 19 min, while the time for kinematic PPP to converge within 20 cm is less than 17 min, 16 min, and 23 min.

Keywords: Polar region · BeiDou navigation satellite system · Precise point positioning · Convergence time

1 Introduction

In recent years, global warming and the melting of ice and snow at the poles have intensified, which not only triggered a series of extreme weather, but also created conditions for countries to develop and utilize the polar regions [1]. The underground of the two poles is rich in natural resources including important metal minerals such as tin, manganese, iron and gold, mineral resources such as coal, phosphate and peat, as well as rich biological species and a large number of clean energy such as geothermal and wind energy [2]. At the same time, due to the massive melting of sea ice, the availability of the Arctic “Northeast channel” and “Northwest channel” in summer will be greatly increased, and the voyage between Asia, Europe and the Americas will be greatly shortened [3], which will break the original world trade pattern [4].

Driven by huge commercial and geographical values, the bipolar regions are bound to become the focus of scientific research and shipping activities in various countries in the foreseeable future. In order to ensure the safety and convenience of scientific research and commercial activities, accurate and reliable navigation and positioning service is very important.

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On June 23, 2020, the last satellite of Beidou-3 (BDS-3) system was launched. The completion of BDS-3 marks the service scope of BDS has expanded from the Asia Pacific region to the world.In recent years, a lot of researches has been carried out on BDS-3 precise clock estimation [5–7], time group delay (TGD)/differential code bias (DCB) [8, 9], satellite availability [10, 11], positioning and convergence performance [12]. Many studies have also been conducted on the polar region, but most of them are concentrated before the full completion of BDS-3, mainly in the form of simulation [3, 14], and the real-measured data are not used. The rest only use BDS-2 and some launched BDS-3 satellites [13], but not all BDS satellites. Literature [14] uses orbit simulation to simulate BDS-3 satellite, and calculates the navigation performance such as polar satellite visibility, satellite elevation angle and PDOP(position dilution of precision), to which comes the conclusion that the number of available satellites and PDOP value of BDS-3 in the eastern part of polar region are better than GPS. But it does not use the real observation data. In literature [15], the convergence performance, data quality, user equivalent ranging error and pseudorange single point positioning accuracy of BDS-2 and BDS-3 in the polar region are evaluated by using the data of IGMAS (International GNSS monitoring&assessment system), and it is concluded that the positioning performance of BDS-3 is greatly improved on the base of BDS-2. But there are only 3 polar stations selected in the research. The analysis samples are too few to draw a more systematic conclusion, and only the pseudorange single point positioning accuracy is evaluated. Literature [16] focuses on the analysis of the positioning and convergence performance of BDS-3(B1CB2a), and comes to the conclusion that BDS-3(B1CB2a) is better than BDS-2 and BDS-3(B1IB3I). But this research focuses on the analysis and evaluation of BDS-3(B1CB2a) ionospheric-free combination, and does not evaluate the positioning performance under more combinations.

Therefore, it is necessary to evaluate the precise point positioning (PPP) performance of BDS at the polar region. Firstly, this research briefly describes the data selection and processing strategy are introduced. The satellite visibility and PDOP value of BDS system worldwide are then analyzed. The positioning RMS (root mean square) and convergence time of each station are statistically analyzed from the aspects of static and kinematic PPP. The differences of positioning performance in different frequency combinations among the polar region and the middle and low latitudes of the Eastern and Western Hemisphere are emphatically compared, and the reasons for the differences are discussed.

2 Data and Methods

2.1 Data Source

In this paper, the data of 17 IGS stations for 30 days in June 2021 are used for calculation and analysis, including 6 stations in the Arctic, 1 station in the Antarctic, 5 stations in the middle and low latitudes of the Western Hemisphere and 5 stations in the middle and low latitudes of the eastern hemisphere. For the convenience of expression, this paper abbreviates "middle and low latitudes in the western hemisphere" and "middle and low latitudes in the eastern hemisphere" as "western hemisphere" and "eastern hemisphere".

Generally, the north of 67 °N and the south of 67 °S are defined as polar regions, but there are too few optional stations in this range, which is difficult to ensure the reliability of statistical analysis. Therefore, when selecting stations, this research appropriately relaxes the selection conditions and takes the north of 60 °N and the south of 60 °S as the selection conditions.

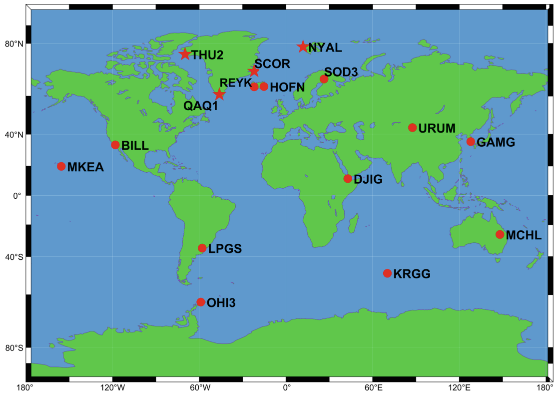

Fig. 1. Monitoring station distribution

In Fig. 1, the stations marked with pentagram can only receive signals from BDS-2 satellites and a small number of BDS-3 satellites, and the stations marked with solid circular can receive signals from BDS-2 satellites and most BDS-3 satellites.

Table 1 specifically shows the satellite PRN (pseudo random noise) that can be received by each station, the number of satellites that can be received, as well as the receiver model, receiver software version and antenna model.

Table 1. Detailed information of the 17 stations

Region	Station	PRN	Num	Receiver type	Version	Antenna type
Polar	HOFN	C06–58	44	LEICA GR50	4.50	LEIAR25.R4
	QAQ1	C06–37	22	SEPT POLARX5	5.4.0	ASH701945E
	REYK	C06–58	44	LEICA GR50	4.50	LEIAR25.R4
	SCOR	C06–37	22	SEPT POLARX5	5.4.0	ASH701941.B
	SOD3	C02–60	50	JAVAD TRE_3 D	4.0.02	JAVRINGANT
	THU2	C06–37	22	SEPT POLARX5	5.4.0	ASH701073.1
	OHI3	C06–58	44	LEICA GR50	4.50	LEIAR25.R4
West	BILL	C11–46	36	SEPT POLARX5	5.4.0	TRM59800.99
	LPGS	C11–58	39	JAVAD TRE_3	3.7.10	JAVRINGANT
	MKEA	C01–59	40	SEPT POLARX5	5.4.0	JAVRINGANT

(*continued*)

Table 1. (*continued*)

Region	Station	PRN	Num	Receiver type	Version	Antenna type
	LMMF	C11–58	39	TRIMBLE ALLOY	5.45	TRM57971.00
	CHPG	C11–58	39	TRIMBLE ALLOY	5.45	TRM59800.00
East	MCHL	C01–60	51	TRIMBLE ALLOY	5.45	TRM59800.00
	GAMG	C01–60	51	SEPT POLARX5TR	5.4.0	LEIAR25.R4
	URUM	C01–60	51	JAVAD TRE_3	3.7.10	JAVRINGANT
	KRGG	C02–60	50	TRIMBLE ALLOY	5.45	LEIAR25.R4
	DJIG	C02–61	51	SEPT POLARX5	5.4.0	TRM59800.00

2.2 Data Processing Strategy

Table 2 shows the data processing strategy of this research. The stations selected in this research all support the B1I, B3I, B1C, and B2a frequency of BDS and the L1, L2 frequency of GPS at the same time. The positioning performance of the ionospheric-free combination of different frequencies of BDS is compared.The selected ionospheric-free combinations include BDS-3(B1IB3I), BDS(B1IB3I), BDS(B1CB2a), BDS(B1CB2a+B1CB3I) and GPS(L1L2). Among them, only BDS(B1IB3I) uses BDS-2 satellites. The remaining BDS combinations all use BDS-3 satellites.

When processing the data, the stochastic model considers errors from the satellite, atmosphere, and receiver [17]. Considering the different accuracy of satellite orbit and clock for different satellite types of BDS, the signal in space range error is set as 2 cm for GEO satellites, and 1cm for IGSO and MEO satellites. For BDS(B1CB2a+B1CB3I) triple-frequency PPP, two ionosphere-free combinations of B1CB2a and B1CB3I are formed, and the inter-frequency clock bias is not considered in this research.

Table 2. Precise point positioning configuration parameters.

Parameter	Solution model or method
Observation	Carrier phase and pseudorange
Parameter estimation method	Kalman filtering
Frequency	BDS(B1I/B3I/B1C/B2a),GPS(L1L2)
Interval	30s
Limited elevation	10°
satellite orbit	GBM precise orbit products
satellite clock	GBM precise clock products
Satellite antenna phase center	Corrected by igs standard

(*continued*)

Table 2. (*continued*)

Parameter	Solution model or method
Receiver antenna phase center	Corrected by igs standard, refer to GPS
Phase winding	Model correction
Earth tide	FES2004 model
Earth rotation	IGS ERP products
Ambiguity	Estimated, constant float parameter
Tropospheric dry delay	Saastamoinen
Tropospheric wet delay	Estimated, random walk
Relativistic effect	Model correction
Receiver clock error	Estimated, white noise

The comparison between BDS-3(B1IB3I) and BDS(B1IB3I) can present the difference in positioning performance due to the addition of BDS-2 satellites under the same frequency combination. The comparison between BDS-3(B1IB3I) and BDS(B1CB2a) can show the differences between different frequency combinations when the satellites are the same. BDS(B1CB2a+B1CB3I), as a three-frequency combination, which introduces more observation information can be used to analyze whether this combination will improve positioning accuracy or reduce convergence time.

All calculations in this paper are completed by Net_Diff developed at the GNSS analysis center of Shanghai Astronomical Observatory, Chinese Academy of Sciences (http://202.127.29.4/shao_gnss_ac/Net_diff/Net_diff.html).

3 Satellite Distribution

3.1 Visible Satellite

Due to the consistence of GEO and IGSO, the visible satellites of BDS are unevenly distributed all over the world, showing the characteristics of more in Asia Pacific and less in Americas.

Figure 2 shows the global distribution of the mean number of BDS visible satellites in the whole week from June 15 to June 22, 2021, with a resolution of 1° by 1°.

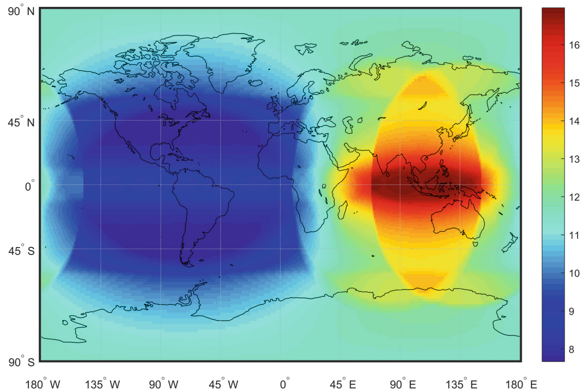

Fig. 2. Average satellite number distribution of BDS from DOY 166 to 173, 2021

Figure 3 shows the average visible satellites numbers in 30 days at the 17 stations. Among them, the global distribution of GPS is relatively even, basically maintaines between 8 and 10, with the exception of LPGS, which is less than 8. According to the analysis, there is a data abnormal with the data at station of LPGS. At the condition of low elevation, the data of this station is frequently interrupted.

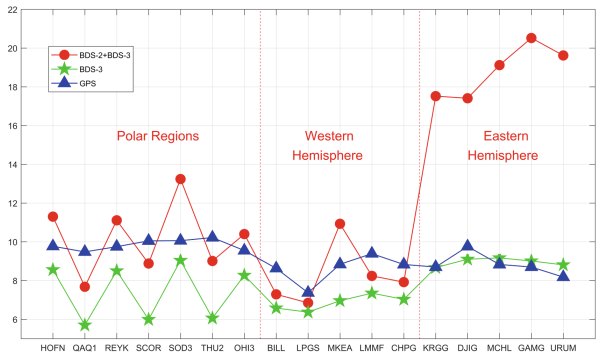

Fig. 3. Number of visible satellites at various stations around the world, the 30-day mean

3.2 PDOP

PDOP (position differentiation of precision) is an important index to evaluate the positioning accuracy. A smaller PDOP value means better satellite constellation spatial configuration and smaller positioning error. Figure 4 shows the average distribution of global PDOP of BDS from June 23 to June 30, 2021.

Similar to the distribution of visible satellites, the PDOP value in the eastern hemisphere is generally smaller than that in the western hemisphere. The PDOP value in the polar region of the eastern hemisphere is between 1.1–2.1, and that in the polar region of the western hemisphere is between 1.8–2.2.

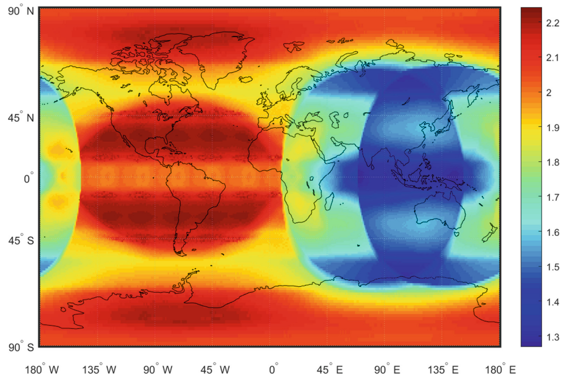

Fig. 4. Average PDOP distribution map of BDS from DOY 166 to 173, 2021

4 Positioning Performance

4.1 Accuracy

In order to evaluate the PPP performance of BDS in the polar region, the 30-day average values of 17 stations in RMS are calculated and compared. The static PPP takes the absolute value of the deviation in the last epoch of the day as the RMS of the day, and the kinematic PPP takes the RMS of the positioning deviation in the period from convergence to the last epoch as the RMS of the day. This paper takes the weekly solution provided by IGS as reference.

From the perspective of different distribution regions, the positioning accuracy of static PPP varies little globally. In order to better understand the global distribution of static PPP positioning accuracy, Fig. 5 counts the RMS mean values of different regions in the three-dimensional direction. It is worth noting that,THU2, SCOR, QAQ1 and LPGS are not included in this statistics.

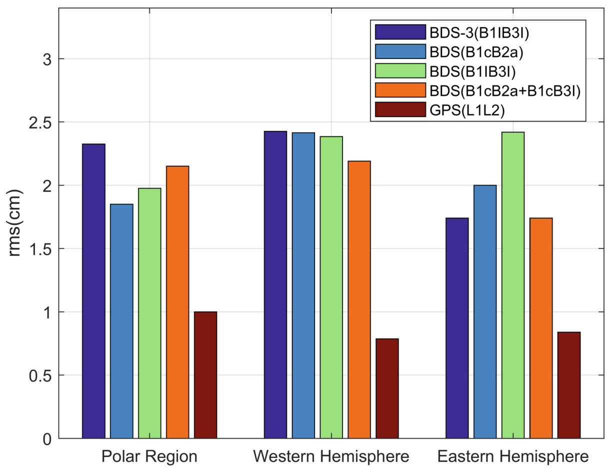

Fig. 5. The RMS statistical results of five static PPP solutions for different region

According to Fig. 5, GPS still has the highest positioning accuracy in the world. This is because that GPS has the advantage of monitoring stations around the world, which can ensure higher orbit and clock accuracy. If only analyze the four combinations of BDS, the gap between BDS-3(B1IB3I) in the western hemisphere with the worst accuracy and BDS-3(B1IB3I) in the eastern hemisphere with the best accuracy is within 1 cm. The distribution of BDS static PPP accuracy is relatively uniform in the world, but there are still some differences. In general, the order of RMS from high to low is western hemisphere > polar region > eastern hemisphere. When focusing on the analysis of the BDS combination in the polar region. The order in RMS is BDS-3(B1IB3I), BDS(B1CB2a+B1CB3I), BDS(B1IB3I) and BDS(B1CB2a). Among them, the accuracy of BDS(B1IB3I) is 13.0% higher than that of BDS-3(B1IB3I). According to Fig. 3, there are about 11 BDS satellites and about 8 BDS-3 satellites in the polar region. Considering that the number of satellites in the polar region is relatively small, the addition of 3 satellites can reasonably explain the improvement of positioning accuracy. Compared with BDS-3(B1IB3I), the accuracy of BDS(B1CB2a) is improved by 21.7%, which may be related to the better signal-to-noise ratio and observation quality of B1C and B2a signals. In the Western Hemisphere, except for the triple-frequency combination of BDS(B1CB2a+B1CB3I), the difference between the other three combinations is very small. Compared with the other three combinations, the accuracy of BDS(B1CB2a+B1CB3I) is improved by 9.7%, 9.3% and 8.2% respectively. This shows that when the number of satellites is less than 10, the triple-frequency combination can obtain better positioning accuracy compared with other combinations because it uses more frequency information and provides more observations. To sum up, the overall accuracy of the ionospheric-free BDS(B1IB3I) compared with the other three BDS combinations is related to the poor orbit and clock error accuracy of BDS-2 satellite [18, 19].

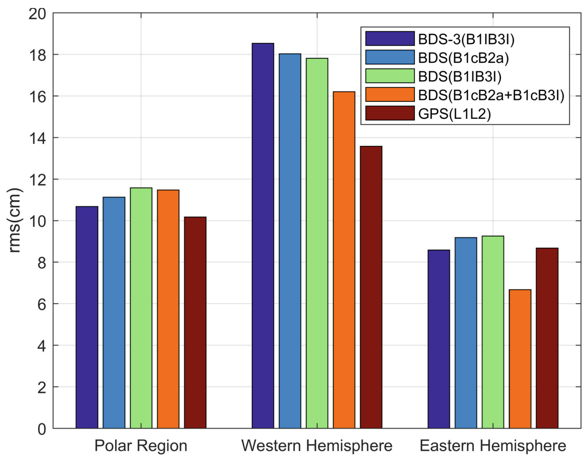

Fig. 6. The RMS statistical results of five kinematic PPP solutions for different region

In aspect of different distribution regions, the positioning accuracy of kinematic PPP varies significantly in different regions of the world. It can be clearly seen that the accuracy of the eastern hemisphere is better than that of other regions as a whole. In order to better understand the global distribution of kinematic PPP positioning accuracy, Fig. 6 explicates the mean RMS values of different regions in the three-dimensional direction. It is worth noting that THU2, SCOR, QAQ1 and LPGS are not included here.

As shown in Fig. 6, the kinematic PPP positioning accuracy is highly correlated with the regional location. Overall, the RMS in different regions from high to low is the Western Hemisphere > polar region > Eastern Hemisphere. The mean RMS of the four BDS combinations is 17.6 cm in the Western Hemisphere, 11.2 cm in the polar region and 8.4 cm in the eastern hemisphere. When focusing on the polar region, the accuracy of GPS is the highest, but the improvement compared with BDS is very limited. The accuracy of GPS(L1L2) is only improved by 4.7% compared with BDS-3(B1IB3I). Among the four BDS combinations, the RMS from high to low is BDS(B1IB3I), BDS(B1CB2a, B1CB3I), BDS(B1CB2a) and BDS3(B1IB3I). The BDS-3(B1IB3I) with the best accuracy is only 7.8% higher than the BDS(B1IB3I) with the worst accuracy, about 1 cm. In the Western Hemisphere, the performance of BDS(B1CB2a, B1CB3I) is better than other BDS combinations, and the accuracy is improved by 12.6%, 10.1% and 9.1% respectively compared with the other three combinations. The triple-frequency combination has great advantages in areas with less satellites.

4.2 Converge Time

The convergence speed is related to the accuracy of observations. At the same time, the change of constellation space geometry caused by satellite motion will also affect the convergence time.

Figure 7 shows the mean statistical result of convergence speed of stations in different regions under the static PPP mode. The threshold of static PPP convergence is that the positioning error in the three-dimensional direction is reduced to less than 10 cm and kept within 10 cm for 20 epochs.

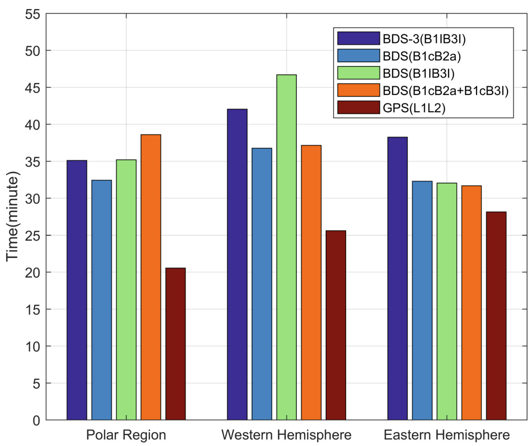

Fig. 7. The average converge time results of five static PPP solutions for different region

When the four BDS combinations are compared, in the polar region, the convergence speed from fast to slow is BDS(B1CB2a), BDS-3(B1IB3I), BDS(B1IB3I), BDS(B1CB2a, B1CB3I), and all are more than 32 min. In the Western Hemisphere, the convergence speed from fast to slow is BDS(B1CB2a), BDS(B1CB2a+B1CB3I), BDS-3(B1IB3I) and BDS(B1IB3I), all of which are more than 35 min. In the eastern hemisphere, the convergence speed from fast to slow is BDS(B1CB2a+B1CB3I), BDS(B1CB2a), BDS(B1IB3I) and BDS-3(B1IB3I), all of which are more than 30 min. Overall, the convergence speed of BDS(B1CB2a) has advantages compared with the other combinations.

Figure 8 shows the mean statistical result of convergence speed of stations in different regions under the kinematic PPP mode. The threshold of kinematic PPP convergence is that the positioning error in the three-dimensional direction is reduced to less than 20 cm and kept within 20 cm for 20 epochs.

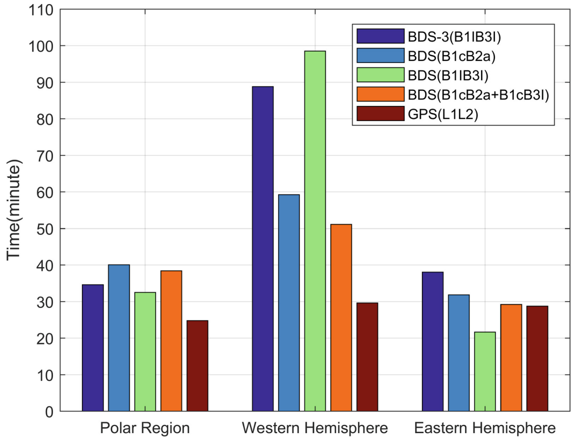

Fig. 8. The average converge time results of five kinematic PPP solutions for different region

GPS is faster than BDS in the polar region and the Western Hemisphere, but it is about 8 min slower than BDS(B1IB3I) in the eastern hemisphere. More BDS satellites and complex geometric and spatial configurations in the middle and low latitudes of the eastern hemisphere greatly shorten the convergence speed of BDS. In the polar region, the convergence time of BDS(B1IB3I) is also the shortest, which may be related to the addition of BDS-2 satellite. In the Western Hemisphere, the B1CB2a combination is far better than B1IB3I combination.

5 Discussions

With the number of stations supporting BDS multi-frequency signals increases in the future, the following points can be further studied:

- According to the distribution of the number of visible satellites, the number of visible satellites in the polar region of the eastern hemisphere is more than that in the Western Hemisphere, which will cause differences in positioning performance. In the future, the positioning performance between the eastern and western hemispheres of the polar region can be compared and studied.
- Although the spatial distribution of BDS is symmetrical, there are differences in climate and environment between the north and south poles. In the future, the differences in positioning performance between the north and south poles can be studied.
- This paper focuses on the impact of the number of visible satellites and constellation geometric space configuration on precision positioning, and does not study its impact on polar positioning from the aspects of signal-to-noise ratio and multipath of satellite signals, which can be further studied in the future.

6 Conclusion

Using the 30-day observation data of 17 IGS stations, this paper focuses on some key problems of BDS-2 and BDS-3 in realizing PPP in the polar region. The conclusions are as follows:

- With the completion of BDS-3, the PDOP value of the visible satellite number of BDS in the world has met the requirements of precision positioning, and can be accurately positioned independently without relying on other GNSS systems. However, due to constellation design, the number of visible satellites of BDS in the world presents the state of middle and low latitudes in the eastern hemisphere > polar regions > middle and low latitudes in the Western Hemisphere, and the PDOP value presents the state of middle and low latitudes in the eastern hemisphere < polar regions < middle and low latitudes in the Western Hemisphere.
- For BDS, in general, the order of accuracy in different regions of the world from high to low is the eastern hemisphere, polar region and Western Hemisphere, and the order of convergence speed from fast to slow is the eastern hemisphere, polar region and Western Hemisphere.
- In the polar static PPP, BDS(B1CB2a) has the highest positioning accuracy and the fastest convergence speed. In the polar kinematic PPP, BDS-3(B1IB3I) has the highest positioning accuracy and the second fastest convergence speed.
- Among the static and kinematic PPP in the western and eastern hemisphere, BDS(B1CB2a, B1CB3I) has the highest positioning accuracy, and BDS(B1CB2a, B1CB3I) has the fastest convergence speed. Triple-frequency ionospheric-free combination has obvious advantages in middle and low latitudes.

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