Interoperability Feasibility Analysis Between Beidou and GPS

Xiaochun Lu, Jun Lu, Xue Wang, Yan Bai and Tao Han

Abstract Interoperability has become a focus of Global Navigation Satellite System (GNSS) and a development aspect, and incurs much focus among the world. For the purpose of maximum benefit, a series of interoperability researches and cooperation are putting forward. In this paper, according to the development of Beidou and GPS, we analyzed the interoperability feasibility between them as three phases. First of all, we introduced the signal plane of Beidou and GPS, separated their interoperability into three phases. After that, we analyzed the signal performance and service performance during each phases. Finally, based on the analyzing results, we offer a reference for Beidou signal design.

1 Introduction

Interoperability has become a focus of Global Navigation Satellite System (GNSS) and a development aspect, and incurs much focus among the world [1]. For the purpose of maximum benefit, a series of interoperability researches and

X. Lu · X. Wang · Y. Bai · T. Han (✉)
National Time Service Center, 710600 Xi'an, People's Republic of China
e-mail: hantao@ntsc.ac.cn

X. Lu · X. Wang · Y. Bai · T. Han
Key Laboratory of Precision Navigation and Timing Technology,
Chinese Academy of Sciences, 710600 Xi'an, People's Republic of China

J. Lu
Beijing Institute of Tracking and Telecommunications Technology,
No. 26 Beiqing Road, Haidian District, Beijing, China

Y. Bai
Graduate School of the Chinese Academy of Science, 100040 Beijing,
People's Republic of China

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Table 1 Signal in the second and third phase of Beidou

Phase	Beidou second	Beidou third
Signal	B1(I)	B1x/y
Center frequency (MHz)	1561.098	1575.42
Code rate (MHz)	2.046	1.023
Modulation	BPSK	TMBOC(6,1,4/33) + BOC(1,1)
Services	Open	Open

Table 2 Signal of current GPS and future GPS

Phase	Current GPS	Future GPS
Signal	L1C/A	L1 C
Center frequency (MHz)	1575.42	1575.42
Code rate (MHz)	1.023	1.023
Modulation	BPSK	TMBOC(6,1,4/33) + BOC(1,1)
Services	Open	Open

cooperation are putting forward. Research of interoperability includes both technical factors, such as signal design, satellite payload, user terminal; and non-technical factors, like market and industry. It should consider not only combining with other systems, but also vindicate own benefits and keep some independence. Thus, research of interoperability should act premeditated, arranged, approached with consider of both technical factors and non-technical factors [2–5].

In this article, we first introduced in development of navigation signal in Beidou and GPS; and separated the interoperability process between then into three steps. Then we analyzed the feasibility of their interoperability in each step. At last, suggestions of Beidou construction and signal system design are given.

2 Discussion of Interoperability Phases Between Beidou and GPS

2.1 Open Signals

Civil signal in GPS L1 band is C/A code-BPSK(1); future civil signals in L1 band is MBOC (TMBOC in pilot channel and BOC(1,1) in data channel).

Civil signal in the second phase of Beidou is BPSK(2), and provides the service in the important area (30E–180E, 70S–70N); civil signal in the third phase is MBOC (TMBOC in pilot channel and BOC(1,1) in data channel) (Tables 1, 2).

Now Beidou system has launched eight satellites of phase-2 and primary formed the positioning ability. Domestic industries have designed CMOS chip in L1 band (1561.098 and 1575.42 MHz); and they planed to produce receivers that

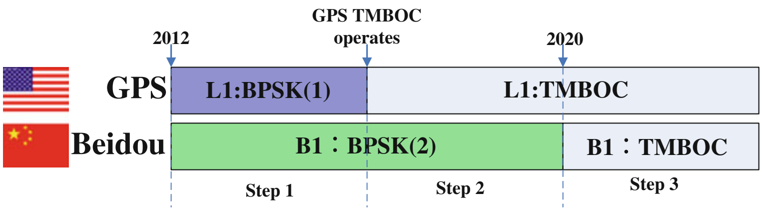

Fig. 1 Phases of interoperability between Beidou and GPS

able to receive GPS L1 C/A and Beidou B1 BPSK(2), which make base of interoperability.

2.2 Suggestion of Interoperability Between Beidou and GPS

According to current resources, interoperability between Beidou B1 and GPS L1 should be operated in three phases (Fig. 1).

- Phase 1: interoperability between BPSK(1) in GPS L1 band (1575.42 MHz) and BPSK(2)-I in Beidou regional system B1 band (1561.098 MHz);
- Phase 2: interoperability between TMBOC in GPS L1 band (1575.42 MHz) and BPSK(2)-I in Beidou regional system B1 band (1561.098 MHz);
- Phase 3: interoperability between TMBOC in GPS L1 band (1575.42 MHz) and TMBOC in Beidou global system B1 band (1575.42 MHz).

3 Feasibility Analysis of Interoperability in Phase 1

In phase 1, Beidou uses B1 BPSK(2)-I signal with a regional constellation; GPS uses BPSK(1) signal with the current constellation including 30 satellites.

3.1 Signal Performance Analysis

3.1.1 Gabor Bandwidth

Gabor bandwidth is the best index to estimate the infection from receive-bandwidth to tracking accuracy; the more Gabor bandwidth is, the better tracking accuracy a signal has. Under the same code loop bandwidth and same receive carrier to noise ratio, the Root Mean Square (RMS) code tracking accuracy depends on RMS bandwidth:

Table 3 Gabor bandwidth

Modulation	Gabor bandwidth	Modulation	Gabor bandwidth
BPSK(1)	1.4415×10^5	CBOC−	3.5348×10^5
BPSK(2)	2.0525×10^5	TMBoc	3.552×10^5
CBOC+	3.5348×10^5	BOCsin(2,2)	3.5558×10^5

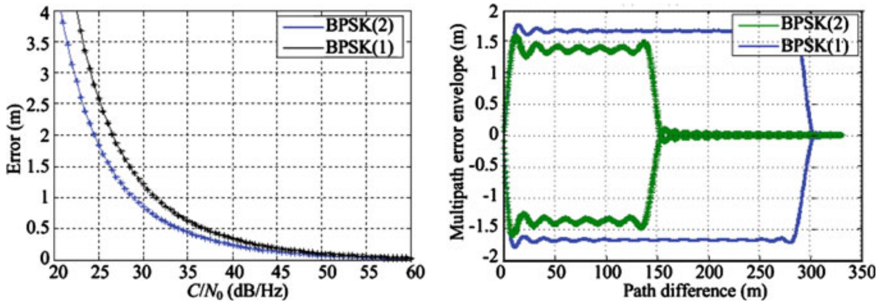

Fig. 2 Tracking error (*left*), multipath error (*right*) of BPSK(1) and BPSK(2)

$$\beta_{rms} = \sqrt{\int_{-\beta_r/2}^{\beta_r/2} f^2 G_S(f) df}. \quad (1)$$

β_{rms} is RMS bandwidth (namely Gabor bandwidth), β_r is bilateral receive bandwidth, $G_S(f)$ is PSD. The RMS bandwidth of different modulations is shown in Table 3.

3.1.2 Tracking Error

$$\sigma_{NELP}^2 = \frac{B_L(1 - 0.25B_L T)\int_{-\beta_r/2}^{\beta_r/2} G_S(f)\sin^2(\pi f \Delta)df}{\frac{C}{N_0}\left(2\pi\int_{-\beta_r/2}^{\beta_r/2} f G_S(f)\sin(\pi f \Delta)df\right)^2} \times \left[1 + \frac{\int_{-\beta_r/2}^{\beta_r/2} G_S(f)\cos^2(\pi f \Delta)df}{T\frac{C}{N_0}\left(\int_{-\beta_r/2}^{\beta_r/2} G_S(f)\cos(\pi f \Delta)df\right)^2}\right], \quad (2)$$

$G_S(f)$ is signal power spectrum, C/N_0 denotes carrier wave-noise ratio, β_r is forward bandwidth, B_L is circle bandwidth, T is integral time, Δs correlator pace (unit: second). From Fig. 2, we know that BPSK(2) has better tracking error than BPSK(1).

3.1.3 Multipath

Receive signal with multipath can be equal as:

$$r(t) = a_0 e^{j\varphi_0} x(t - \tau_0) + \sum_{n=1}^{N} a_n e^{j\varphi_n} x(t - \tau_n). \tag{3}$$

where a_0 is the extent of firsthand signal; φ_0 is the phase of firsthand signal; $x(t)$ is the complex envelope of sending signal; τ_0 is the time delay of firsthand signal; N is the number of path of multipath signal; a_n is the extent of multipath signal; φ_n is the phase of multipath signal; τ_n is the time delay of multipath signal. Multipath error can be depicted as:

$$\varepsilon_\tau \approx \frac{\pm \tilde{a}_1 \int_{-\beta_r/2}^{\beta_r/2} S(f) \sin(2\pi f \tilde{\tau}_1) \sin(\pi f d) df}{2\pi \int_{-\beta_r/2}^{\beta_r/2} f S(f) \sin(\pi f d)[1 \pm \tilde{a}_1 \cos(2\pi f \tilde{\tau}_1)] df}. \tag{4}$$

where, $\tilde{a}_1 = a_1/a_0$ is the extent ratio from multipath signal to firsthand signal, d is correlator space.

The mean multipath error $A(\tau)$ can be calculated by:

$$A(\tau) = \frac{1}{\tau} \int_0^\tau |\max(E(x)) - \min(E(x))| dx, \tag{5}$$

where $E(x)$ is the curve function of multipath error envelope, τ is code time delay. Then the even multipath error is:

$$\varepsilon_a(\tau_1) = \frac{1}{\tau_1} \int_0^{\tau_1} \left[\frac{\left| \varepsilon(\tau)|_{\varphi=0} \right| + \left| \varepsilon(\tau)|_{\varphi=180} \right|}{2} \right] d\tau, \tag{6}$$

where $\varepsilon(\tau)$ is the function of multipath error envelope, $\varepsilon_a(\tau_1)$ is the function of even multipath error, τ_1 and τ are multipath signal time delay. Suppose the receiver front bandwidth is $B = 30$ MHz; correlator space is $d = 1/20$ chip; extent ratio from multipath signal to firsthand signal is $a_1 = -5$ dB [see Fig. 2 (right)].

3.1.4 Code Cross-Correlation

Code cross-correlation can validate the cross-correlation between Beidou ranging code and GPS L1 C/A code. Simulate the maximum value after uniformed correlation between 32 GPS codes to 32 GPS codes, 13 Beidou codes to 13 Beidou codes and 32 GPS codes to13 Beidou codes (Fig. 3).

Beidou B1 BPSK(2) signal has a better tracking performance, better anti-jamming performance and better anti-multipath performance than GPS C/A signal.

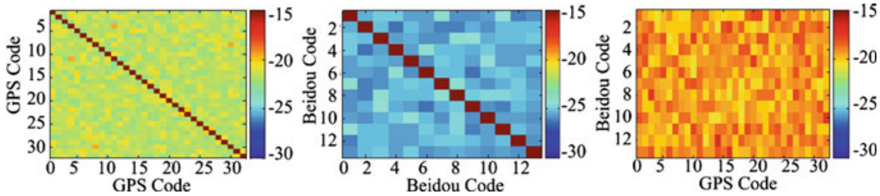

Fig. 3 Cross-correlation of GPS ranging code (*left*), Beidou ranging code (*middle*), GPS ranging code and Beidou ranging code (*right*)

Interoperability of the two signals makes a higher receiver ranging accuracy. Interoperability among the two signals does not rises to much receiver complexity, while enhances the service performances for users.

3.2 Analysis of Service Performance

3.2.1 Accuracy

Service accuracy is employed to depict the difference between the real value and measurement value of positioning, timing and velocity measure [6]. Space signal accuracy includes User Range Error (URE), User Range Ratio Error (URRE), User Range Acceleration Error (URAE) and User Timing Error. It is an important index in assessment the contribution of satellite ephemeris and forecasted clock error to users' positioning error, velocity error and timing error. Assessment of space signal accuracy requires the exactitude orbit and clock error.

Theoretically, the positioning error is depends on pseudo range measurement noise, satellite location error and Positioning Dilution of Precision (PDOP).

$$\sigma_u = \mathrm{PDOP} \times \sigma \tag{7}$$

where PDOP is a non-randomly factor which determines by the location of user and satellites; σ is related to URE and is a randomly factor.

Service accuracy is the difference between users' real position, velocity, timing value and their measurements. Accuracy = UERE × PDOP, where UERE is make up of URE and UEE ($UERE = \sqrt{(URE)^2 + (UEE)^2}$); UERE is related with satellite clock error, ephemeris error, atmosphere model error, multipath error and receiver clock error. In a given system, with the same URE and same UEE, the positioning accuracy is determined by PDOP.

3.2.2 Availability

Service availability is the time ratio of congruous threshold value of positioning, timing, velocity measurement in a prescriptive time period (usually a recursive period) and a given region.

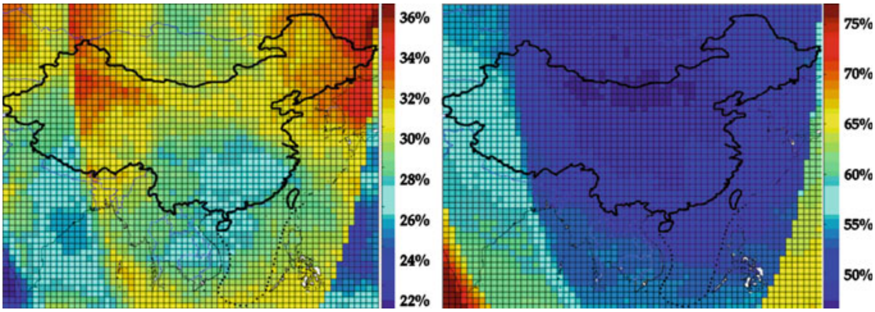

Fig. 4 Average PDOP reducing in China [compare with GPS (*left*), Beidou (*right*)]

Suppose the threshold of positioning accuracy and timing accuracy are σ_p, σ_t. The URE is related to positioning accuracy:

$$\sigma_p = \sqrt{g_{11} + g_{22} + g_{33}} \times \mathrm{URE} = \mathrm{PDOP} \times \mathrm{URE}. \tag{8}$$

Timing accuracy is (GPS SPS 2008):

$$\sigma_t = \sqrt{g_{44}} \times \Delta t = \mathrm{TDOP} \times \Delta t = \frac{\mathrm{TDOP} \times \mathrm{URE}}{c}, \quad (c \text{ is velocity of light}). \tag{9}$$

Thus, the threshold of positioning accuracy and timing accuracy in a given system is:

$$\begin{pmatrix} \sigma_P \\ \sigma_t \end{pmatrix} = \begin{pmatrix} \mathrm{PDOP} \\ \mathrm{TDOP} \div c \end{pmatrix} \times \mathrm{URE}. \tag{10}$$

For the same threshold of positioning accuracy and timing accuracy, debasement of PDOP and TDOP will help to add the threshold. Because the range of URE with randomicity will be enlarged, which leads the enhancement of GNSS availability, this extension is related with the distribution of URE.

3.2.3 Simulation

Calculate average PDOP, TDOP of interoperability constellation, GPS constellation, Beidou constellation in 7 days (a return period) point by point both in the region of China and U.S. Then compare their average to solely system, as follows:

From the simulation results:

- In China, the average PDOP reducing from interoperability constellation to GPS is 29.01%, the average TDOP reducing is 25.77%; so positioning accuracy and availability will add 29.01%, timing accuracy and availability will add 25.77% (Fig. 4).
- In China, the average PDOP reducing from interoperability constellation to Beidou is 53.33%, the average TDOP reducing is 61.23%; so positioning

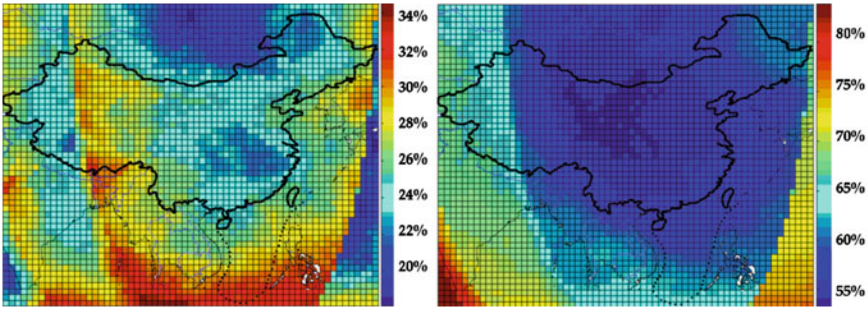

Fig. 5 Average TDOP reducing in China [compare with GPS (*left*), Beidou (*right*)]

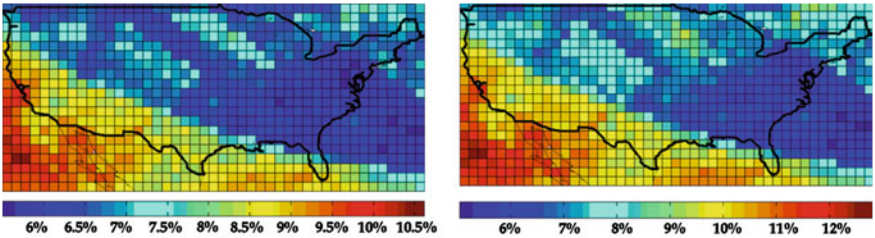

Fig. 6 Average PDOP (*left*), TDOP (*right*) reducing in the U.S. (compare with GPS)

accuracy and availability will add 53.33%, timing accuracy and availability will add 61.23% (Fig. 5).

- In the U.S., the average PDOP reducing from interoperability constellation to GPS is 7.26%, the average TDOP reducing is 8.04%; so positioning accuracy and availability will add 7.26%, timing accuracy and availability will add 8.04% (Fig. 6).

4 Feasibility Analysis of Interoperability in Phase 2

In phase 2, Beidou uses B1 BPSK(2)-I signal with a regional constellation; GPS uses TMBOC signal with the current constellation including 30 satellites.

4.1 Signal Performance Analysis

Figure 7 (left) shows the correlation peak curve of TMBOC and BPSK(2); where TMBOC has the most sharp correlation peak; and from Fig. 7 (right), it shows that TMBOC has a less tracking error than BPSK(2).

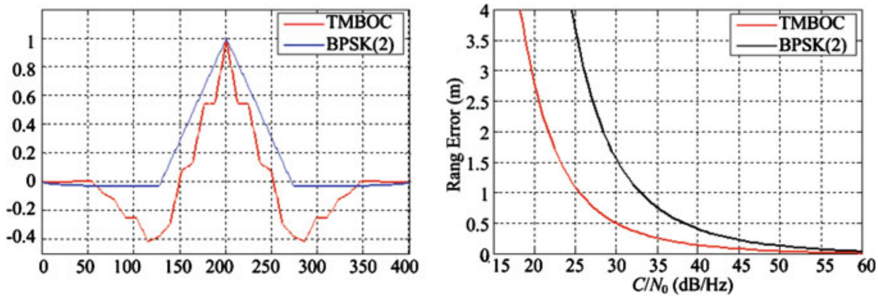

Fig. 7 Correlation peak (*left*), tracking error (*right*) of BPSK(2) and TMBOC

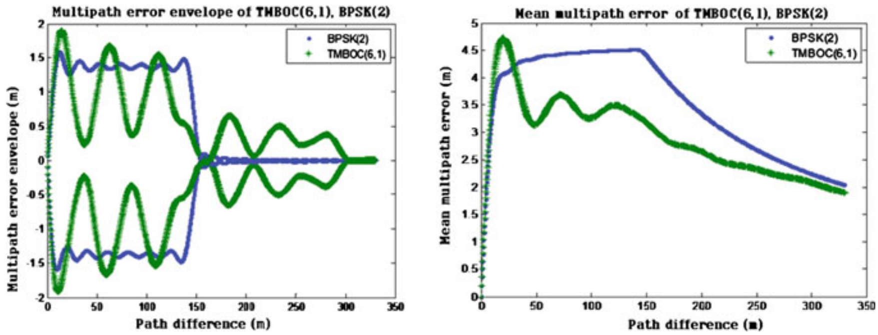

Fig. 8 Multipath error envelope (*left*), multipath error (*right*) of BPSK(2) and TMBOC

GPS TMBOC has better ranging accuracy, anti-jamming and anti-multipath than Beidou B1 BPSK(2), but the difference is not big. Interoperability at different frequency improves the anti-jamming and availability of system (Fig. 8).

4.2 Analysis of Service Performance

Satellite constellation in phase 1 and 2 are the same, so the service performance change will be the same:

- In China, the average PDOP reducing from interoperability constellation to GPS is 29.01%, the average TDOP reducing is 25.77%; so positioning accuracy and availability will add 29.01%, timing accuracy and availability will add 25.77%.
- In China, the average PDOP reducing from interoperability constellation to Beidou is 53.33%, the average TDOP reducing is 61.23%; so positioning accuracy and availability will add 53.33%, timing accuracy and availability will add 61.23%.

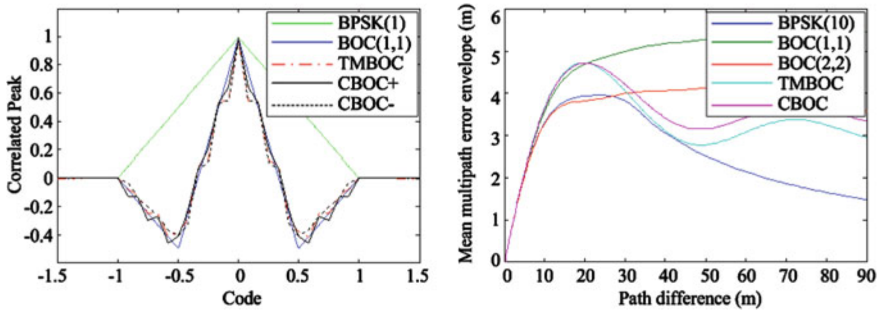

Fig. 9 Correlation peaks (*left*), multipath running average error (*right*) of BPSK, BOC, TMBOC and CBOC

- In the U.S., the average PDOP reducing from interoperability constellation to GPS is 7.26%, the average TDOP reducing is 8.04%; so positioning accuracy and availability will add 7.26%, timing accuracy and availability will add 8.04%.

5 Feasibility Analysis of Interoperability in Phase 3

Navigation signal both of Beidou and GPS in phase 3 is TMBOC; constellation of Beidou is its global constellation while GPS will keep its current constellation.

5.1 Signal Performance Analysis

Correlation peak curve has a direct relation with ranging accuracy, anti-multipath and anti-jamming performance. The sharper the peak, the better performance it has. Figure 9 (left) shows the correlation peak curves of BPSK(1), BOC(1,1), TMBOC and CBOC. Generally, we can get different multipath performance for each kind of navigation signal based on its multipath error and multipath running average error. Assume that receiver front bandwidth is 30 MHz, with correlator space of 1/20 chip and the ratio of multipath to direct path of −6 dB. Figure 9 (right) shows the envelop curves of multipath average errors for BPSK(10), BOC(1,1), BOC(2,2), TMBOC Pilot and CBOC Pilot.

If we put the modulated signal with best performance in the first place, and that with worst performance in the end, then we can easily get the following results: BPSK(10), BOC(2,2), TMBOC(6,1,4/33), CBOC-(6,1,1/11), BOC(1,1), BPSK(1); where the difference between TMBOC(6,1,4/33) and CBOC-(6,1,1/11) is very small.

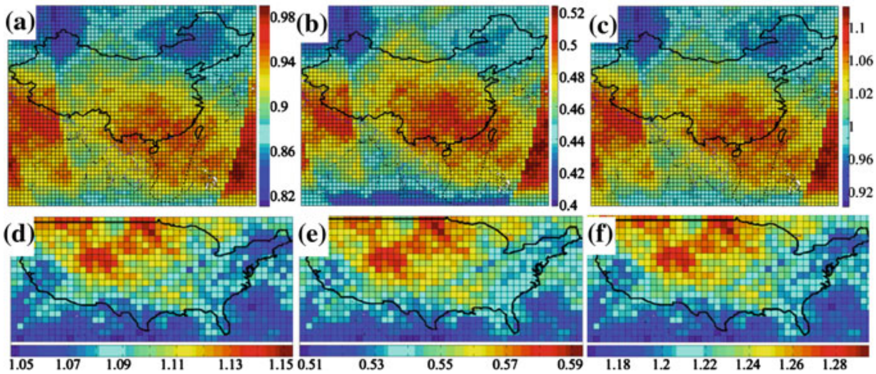

Fig. 10 PDOP in China (**a**), the U.S. (**b**); TDOP in China (**c**), the U.S. (**d**); GDOP in China (**e**), the U.S. (**f**)

Thus, the particular technologies of time division in sub-carrier wave, second coding for ranging codes, channel separation and message coding, make TMBOC signal has a better acquisition performance, better tracking performance, better demodulation performance, better anti-jamming performance and better anti-multipath performance.

5.2 Analysis of Service Performance

In phase 3 of interoperability between Beidou and GPS, not only did the signals of Beidou system change, but also did its satellite constellation.

From the simulation results:

- In China, the average PDOP reducing from interoperability constellation to GPS is 30.14%, the average TDOP reducing is 28.76%; so positioning accuracy and availability will add 30.14%, timing accuracy and availability will add 28.76%.
- In China, the average PDOP reducing from interoperability constellation to Beidou is 17.75%, the average TDOP reducing is 20.14%; so positioning accuracy and availability will add 17.75%, timing accuracy and availability will add 20.14%.
- In the U.S., the average PDOP reducing from interoperability constellation to GPS is 35.10%, the average TDOP reducing is 36.66%; so positioning accuracy and availability will add 35.10%, timing accuracy and availability will add 36.66%.
- In the U.S., the average PDOP reducing from interoperability constellation to Beidou is 35.86%, the average TDOP reducing is 37.97%; so positioning accuracy and availability will add 35.86%, timing accuracy and availability will add 37.97% (Fig. 10).

6 Summary

In this paper, we analyzed the interoperability feasibility among Beidou and GPS in three phases; and we obtain:

1. Beidou and GPS could achieve interoperability;
2. interoperability between Beidou and GPS will be of great benefits to the improvement in service performance;
3. with the development of each system, interoperability between the two systems will deepen;
4. interoperability could be achieved between Beidou B2 signal and GPS L5 signal as well, so dual-frequency interoperability can also be realized.

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