Phase Multipath Detection and Its Effect on Positioning Based on Multi-GNSS

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Abstract. The multipath effect is one of the main error sources of Global Navigation Satellite System (GNSS) positioning. However, due to the complexity of the multipath effect in the time domain and space domain, even with the improvement of multiple systems, the error cannot be eliminated by conventional methods. Nevertheless, the multipath effect will have different effects on carrier phase observations at different frequencies, and the carrier-to-noise-power-density ratio (C/N0) can reflect this effect. Based on this basic idea, scholars have proposed two kinds of multipath detection methods: reference function method and double statistics method. There are significant differences between the constellations and the signal of different systems, it is necessary to demonstrate the different results of the reliability of each system, and then explores the feasibility of using the phase multipath detection method to improve the positioning accuracy. The experimental results show that after two methods have been corrected, the positioning accuracy is significantly improved, and the improvement in the N and E directions is relatively weak, but the improvement in the U direction is particularly obvious: the accuracy of the reference function method correction is increased by 56.00%, and the improvement of the double statistic method correction is 63.19%. At the same time, these two methods can be applied not only to the static, but also to the dynamic real-time domain, providing a new idea for the study of phase multipath.

Keywords: Phase multipath effect · C/N0 · Reference function method · Double statistics method · Multi-GNSS

1 Introduction

With the Chinese BeiDou Navigation Satellite System and the European Union Galileo Satellite Navigation System basically having global service capabilities, enough satellites ensure that GNSS technology can provide higher accuracy for dynamic or static applications. In the actual location of the main error has been eliminated by modeling, filtering or finite difference method [1], such as the satellite clock error modeling, in view of the ionospheric delay effect that using a combination of dual-frequency ionosphere-free combination, in view of the tropospheric delay model has Saastamoinen model and Hopfield model, that are widely used, aiming at possible gross error in observation using Robust Kalman Filtering weakened the impact, combination of double difference can eliminate the receiver error and satellite clock

J. Sun et al. (Eds.): CSNC 2020, LNEE 651, pp. 304–317, 2020.
https://doi.org/10.1007/978-981-15-3711-0_27

error. However, the multipath effect in a complex environment is difficult to be eliminated by the above method, it has been one of the main factors restricting the application of GNSS with high precision [2, 3]. At present, the methods to deal with the multipath effect can be divided into three categories. First, one can be positioned in an open observation environment, which is widely used in the static location. Second, there is a method based on the hardware equipment, then the influence of the multipath effect can be significantly reduced by using a specific antenna that only receives the right polarization signal and rejects the left polarization signal. Third, one can apply advanced data processing methods, such as the sidereal filtering method, which used the repeatability of the satellite's day and night motion to remove high-frequency signals in the coordinate domain or observation domain by low-pass filtering and then calculated multipath signals [4]. The other popular data processing method is the hemispherical map, that the model of the basic idea is when the azimuth and elevation were determined, the multipath effect on the phase observation value is a constant value, and then it can establish multipath error space grid points related to altitude and azimuth [5]. However, none of the above methods can completely satisfy the real-time or dynamic applications.

Based on the correlation between C/N0 and phase multipath, many scholars have proposed different methods to efficiently detect and weaken the multipath effect of carrier phase. Zhang et al. [6] used the signal-to-noise ratio (SNR) to reflect the influence of multipath and improved the positioning accuracy by reducing the weight of multipath observations. Wu et al. [7] proposed the method of using signal-to-noise ratio to correct carrier phase multipath, made a quantitative analysis of the error of multipath effect on phase observation, and preliminarily explored the feasibility of extracting multipath effect from the composite signal. Based on SNR, Bilich et al. [8] used wavelet analysis and map the multipath environment around a station using a power spectrum. Groves et al. [9] proposed a multipath detection method based on C/N0. Strode et al. [10] used the three-frequency SNR to detect multipath: by referring to the reference function method, and under strict statistical significance, they constructed statistics and statistical thresholds through the difference between SNR to detect the existence of the multipath effect. Zhang et al. [1] proposed a new multipath detection method, which is real-time multipath detection of dual-frequency and dual-statistics (double statistic method), and constructed new statistics and statistical thresholds. Spanik et al. [3] proposed an optimal combined multipath detection method based on the reference function method. In this paper, the performance characteristics of the two methods in different systems are tested by using the reference function method and the double statistic method as the basic research methods, and the influence of the multipath detection method on the positioning results is focused on testing. The experimental results prove that it is feasible to improve the positioning accuracy by reducing the multipath error by the SNR. Gao et al. [11] point out when the receiver directly receives the original observation quantity (signal processing algorithms such as data smoothing are forbidden), the SNR and C/N0 have good consistency, so this paper does not distinguish the difference between the two.

2 Effect of Multipath Effect on GNSS Location

Multipath effect refers to that the satellite signals arrive at the receiver antenna through multiple paths, and then the superposition of signals with different phases produces interference and diffraction, which results in the phase delay of the signals received by the receiver, and the multipath error occurs in the phase observation, which seriously affects the positioning accuracy. In the complex environment, especially in the urban environment, the observed values of pseudorange and carrier phase can be affected simultaneously. Since the carrier wavelength is shorter, it is less susceptible to the influence of multipath. Chen et al. [12] proved the maximum multipath error can reach 10 m for GPS P-code. While the maximum can reach about 6 cm for BeiDou B6I band, which is not allowed in high-precision applications. Figure 1 shows the schematic diagram of the principle of observation error caused by multipath, respectively representing interference multipath and diffraction multipath.

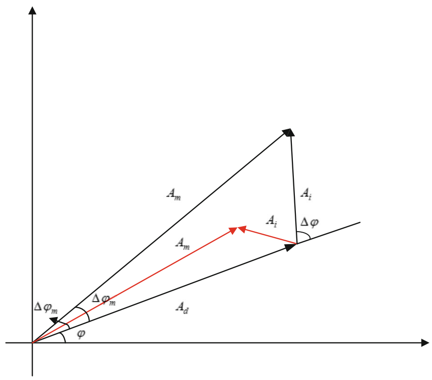

Fig. 1. The inner triangle represents the diffractive phase multipath and the outer triangle represents the interference phase multipath

When the direct signal is $S_d = A_d \cos\varphi$ and the reflect signal $S_r = \alpha A_d \cos(\varphi + \theta)$, then the received signal expression as below

$$S_c = S_d + S_r = A_d \cos\varphi + \alpha A_d \cos(\varphi + \theta) \tag{1}$$

where A_d and φ denote the amplitudes of the phase of the direct signal, respectively, θ denotes the phase shift delayed by the indirect signal, and α denotes the reflection coefficient. It leads to the relations as follows

$$\begin{aligned} S_c &= \lambda A_d \cos(\varphi + \omega) \\ \lambda &= \sqrt{1 + 2\alpha \cos\theta + \alpha^2} \\ \omega &= \arctan\left(\frac{\sin\theta}{\alpha^{-1} + \cos\theta}\right) \end{aligned} \tag{2}$$

Where ω is the carrier phase error caused by the multipath effect, which can be seen from the above formula: while α is equal to 1 and θ is equal to $\pi/4$, the ω gets the maximum quarter cycle

3 Carrier Phase Multipath Detection Method

3.1 Reference Function Method

First of all, in the signal propagation process, if there is a multipath effect, it will have different effects on the SNR at different frequencies. According to this basic idea, after differentiating the SNR at different frequencies, a detection statistic about the SNR can be constructed S, and then compare it with the statistical threshold, to determine if there is a multipath error. The function model can be described as follow

$$S_r^s = \sqrt{\left(s_r^{s,L1} - s_r^{s,L2} - \Delta s_r^{1,2}\right)^2 + \left(s_r^{s,L1} - s_r^{s,L3} - \Delta s_r^{1,3}\right)^2} \quad (3)$$

Where the superscript donates the satellite and frequency, the subscript donates the receiver, s represents the SNR observation, and Δs represents the C/N0 frequency the difference function of the elevation predicted from a low multipath environment. If dual frequency data is only used, Eq. (3) can further simplify Eq. (4)

$$s_r^s = \left|s_r^{s,L1} - s_r^{s,L2} - \Delta s_r^{1,2}\right| \quad (4)$$

Where it can be seen that statistics can still be constructed using dual-frequency data, but for a certain reflection path delay, if the phase lag between the two frequencies is the same, the disturbance after the SNR is not obvious. Therefore, this method will fail when multipath has similar effects on the dual-frequency SNR, but statistics based on tri-frequency data can greatly reduce this probability, making detection of multipath effects more reliable, but this also increases hardware costs.

The statistical threshold is determined by the statistic S calculated in the low multipath environment. First, calculate the statistic S in the supposed multipath-free environment, and then use a polynomial about the elevation to fit the statistic. The order of the polynomial can be determined experimentally. In this paper, a third-order polynomial is selected and then calculated. The corresponding standard deviation is finally combined with the observed values in the multipath environment, and finally, the statistical threshold T can be determined. Depending on the selected standard deviation, there can be three different expressions T_σ $T_{2\sigma}$ $T_{3\sigma}$, the general form is as below

$$T(\theta) = \hat{S}(\theta) + t \cdot \overset{\wedge}{\sigma}_s \quad (5)$$

Where T donates threshold, θ donates the elevation, and t donates coefficient (the value is one, two or three)

3.2 Double Statistic Method

This is a real-time carrier phase multipath detection method based on dual-frequency. Compared with the reference function method, this method is different in that it uses only dual-frequency data and constructs two statistics. It is also suitable for three frequency, therefore the double statistic method can not only reduce the hardware requirements but also improve the reliability of detection. The function model formula of this method is as below.

$$\begin{aligned} S1 &= \sqrt{\left[S_1(\theta_r^s) - S_1^*(\theta_r^s)\right]^2 + \left[S_2(\theta_r^s) - S_2^*(\theta_r^s)\right]^2} \\ T1 &= \beta\sqrt{\left[\sigma_1(\theta_r^s)\right]^2 + \left[\sigma_2(\theta_r^s)\right]^2} \end{aligned} \tag{6}$$

Where $S1$ donates the first statistic, S^* represents the reference function about the elevation obtained from the low multipath environment, the $T1$ donates the threshold, σ is the standard deviation, and β ($\beta = 1, 2, 3$) is the proportionality coefficient.

$$\begin{aligned} S2 &= \left|\Delta S_{12} - \Delta S_{12}^*\right| \\ T2 &= \gamma\sigma_{12}(\theta_r^s) \end{aligned} \tag{7}$$

Where the $S2$ donates the second statistic, ΔS_{12} and ΔS_{12}^* donates the difference between SNR in multipath environment and the reference function obtained from the low multipath surroundings, respectively, γ is scale factor, σ_{12} is function of elevation and $T2$ donates the second threshold.

4 Pseudorange Multipath

The calculation formula of pseudorange multipath has been widely used in the quality analysis software TEQC. It is essentially a combination of free geometry and free ionosphere. The common form is as below:

$$CMC_i = P_i - \frac{1+\alpha}{1-\alpha}\phi_i + \frac{2\alpha}{1-\alpha}\phi_j - b_i \tag{8}$$

Where the i and j donates different frequencies, P represent the pseudorange observation and the ϕ is carrier phase observation, α represent the square ratio of the frequency, and b represent the deviation term, which mainly includes hardware delay and multipath. Taking the mean value as a constant over a while, and then subtract the constant, the remaining part contains pseudorange multipath and carrier phase multipath, and the carrier phase multipath is much smaller than pseudorange multipath, so it mainly reflects the pseudorange multipath measurement [13].

5 Experimental Data Acquisition

Data acquisition requires the selection of specific experimental sites. In this experiment, the open environment was chosen to be on the roof of the WenFa Building of Central South University (CSU), and the multipath environment was chosen to be next to the innovation park of CSU. The receiver was chosen to be Trimble NetR9. The antenna type was TRM57971.00 (without the radome). Figures 2 and 3 were data acquisition scenarios in the multipath environment and open environment respectively. The Acquisition time was 4 h.

Fig. 2. Multipath environment

Fig. 3. Low multipath environment

6 Experimental Results and Analysis

Since Spanik et al. [3] have pointed out whether the antenna gain is considered or not, it does not effect on the detection results, the effect of the antenna gain on the observation data is not considered in this experiment. Regarding the effect of non-line-of-sight reception (NLOS), in this experiment, it can simply use the elevation and azimuth to determine whether NLOS will occur, and Zhang et al. [1] have pointed out that the effect of NLOS on signals of different frequencies may often be eliminated by the difference of the SNR, and difference can also reduce the impact of the antenna itself. There is the lag of the SNR, which can be processed by statistics of the C/N0 at different frequencies.

6.1 GPS Test

Firstly, GPS is discussed. For the rigor of result comparison, a three-frequency data test is also selected for the double statistic method. The experiment selected the G32 satellite as the reference satellite and the G31 satellite as the experimental satellite. Figures 4 and 5 show the modeling results of SNR, and the function model is shown in Eq. (9), where the unit of elevation is degree. In Figs. 4 and 5, the blue point donates SNR difference, and the red line represents the fit value. The second statistic of the double statistic method is consistent with the modeling process of the reference function method.

$$\begin{aligned}\Delta S_{12} &= 28.0665 - 2.5834\theta + 0.0713\theta^2 - 6.1710 \times 10^{-4}\theta^3 \\ \Delta S_{13} &= 23.6203 - 2.2706\theta + 0.0589\theta^2 - 4.8780 \times 10^{-4}\theta^3\end{aligned} \tag{9}$$

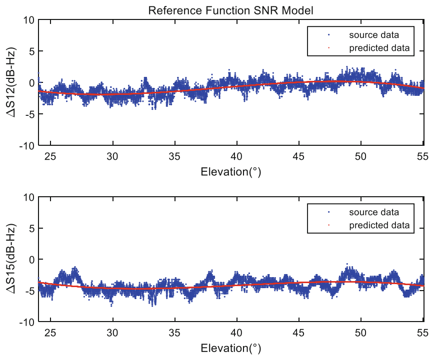

Fig. 4. Reference function method SNR model

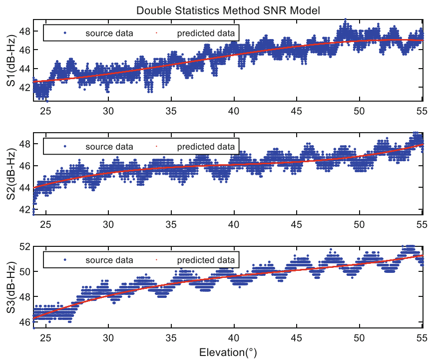

Fig. 5. Double statistic method SNR

Then, the function model of the threshold is determined, and after calculation, the function model is obtained as formula (10).

$$T = 8.6796 - 0.4480\theta + 0.0110\theta^2 - 8.754 \times 10^{-5}\theta^3 \tag{10}$$

The same way is used to determine the parameters of the double statistic, and the function model is as below

$$\begin{aligned}S_1^* &= 49.5420 - 0.8180\theta + 0.0282\theta^2 - 2.5694 \times 10^{-4}\theta^3 \\ S_2^* &= 21.4755 + 1.7654\theta - 0.0432\theta^2 + 3.6016 \times 10^{-4}\theta^3 \\ S_3^* &= 25.9218 + 1.4526\theta - 0.0307\theta^2 + 2.3086 \times 10^{-4}\theta^3 \\ \Delta S_{12}^* &= 28.0665 - 2.5834\theta + 0.0713\theta^2 - 6.1710 \times 10^{-4}\theta^3 \\ \Delta S_{23}^* &= 23.6203 - 2.2706\theta + 0.0589\theta^2 - 4.8780 \times 10^{-4}\theta^3\end{aligned} \tag{11}$$

The function model of the statistical threshold of the double statistic method is Eq. (12)

$$\begin{aligned}\sigma_1 &= 6.4234 - 0.4456\theta + 0.0110\theta^2 - 8.7920 \times 10^{-5}\theta^3 \\ \sigma_2 &= 0.8098 - 0.0345\theta + 9.4563 \times 10^{-4}\theta^2 - 8.1387 \times 10^{-6}\theta^3 \\ \sigma_3 &= -0.2924 + 0.0536\theta - 0.0015\theta^2 + 1.3538 \times 10^{-5}\theta^3 \\ \sigma &= 8.6796 - 0.4480\theta + 0.0110\theta^2 - 8.754 \times 10^{-5}\theta^3\end{aligned} \tag{12}$$

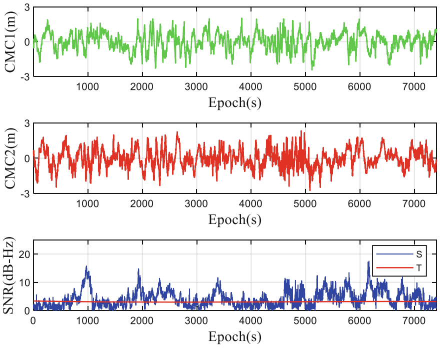

Fig. 6. Reference function detection result

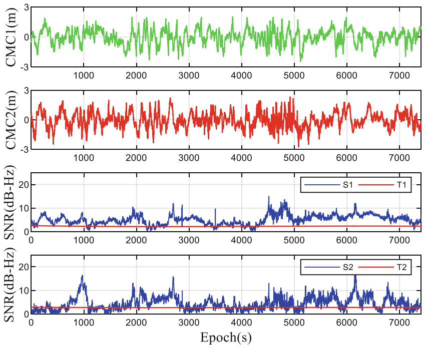

Fig. 7. Double statistic detection result

Then, the statistics in the multipath environment and their corresponding thresholds are calculated. The experimental results are shown in Figs. 6 and 7: CMC stands for pseudorange multipath, S and T stand for statistics and statistical thresholds, respectively. Through the detection results of pseudorange multipath and phase multipath, it is found that the two methods are very consistent with pseudorange multipath in terms of fluctuation and oscillation trend. However, pseudorange multipath and phase multipath are not strictly consistent, which is mainly related to the station environment after analysis. Between 600 s and 1000 s, both detection methods consistently indicate that the phase observed value in this period is polluted by multipath, and the value size of pseudorange multipath in this period is also very consistent with the oscillation trend. Between the 2800 s and 4000 s, the value of pseudorange multipath decrease and lower volatility, reference function method and double system measurement are shown only less phase multipath, two kinds of methods to detect multipath observed value accounted for the proportion of total observations: reference function method detection result is 66.83% and dual system measurement result is 66.77%, the detection results of two methods are especially consistent. Thus, the reference function method and double system measurement in GPS phase multipath detection performance has been pretty, but double constructed two statistics on the metrology system so significantly more robust.

6.2 GALILEO Test

The Galileo was tested following GPS data processing. In the experiment, E02 was selected as the reference satellite to test the E07 satellite observations. The corresponding the SNR must be modeled first. Due to space limitations, SNR modeling results diagram is omitted. The corresponding reference function method function model are Eq. (13), which includes the SNR function model and threshold model, and then it can calculate the function model of the double statistic method, whose function model is omitted due to the space limitations.

$$\Delta S_{12} = 9.5705 - 0.9588\theta + 0.0310\theta^2 - 3.2712 \times 10^{-4}\theta^3$$
$$\Delta S_{13} = 0.9805 - 0.4625\theta + 0.0154\theta^2 - 1.6071 \times 10^{-4}\theta^3 \quad (13)$$
$$T = 0.9805 + 0.9597\theta - 0.0304\theta^2 + 3.0972 \times 10^{-4}\theta^3$$

Finally, the statistics and corresponding statistical thresholds are calculated, and the results are analyzed. Figures 8 and 9 represent the detection results of the reference function method and the double statistics method, respectively.

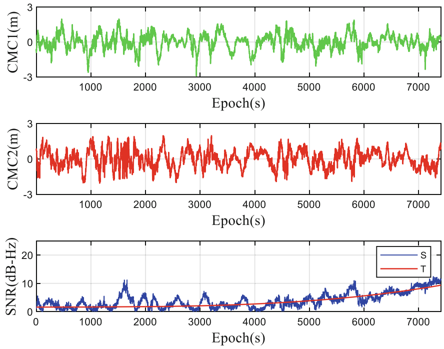

Fig. 8. Reference function detection result

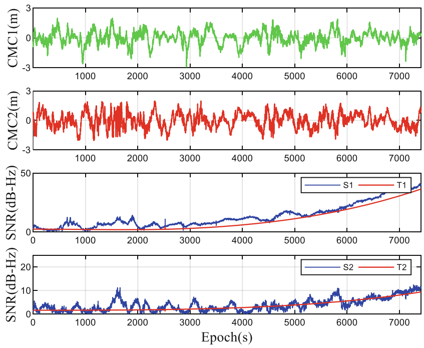

Fig. 9. Double statistic detection result

It can be seen from the experimental results of pseudorange multipath that the observed values of the Galileo have suffered severe multipath effects during this observation period. The peak value of the statistic detected by the reference function method is very consistent with the peak value of pseudorange multipath. The results of the two methods between 6000 s and 7000 s indicate that the phase observations have less multipath interference, while the corresponding two types of pseudorange multipath have smaller values and relatively stable trends. However, the first statistic of the double statistic method during the entire observation period shows that almost all observations are affected by multipath interference during the entire observation period. However, after combining the two statistics, it is found that the proportion of multipath observations is significantly reduced. The proportions of multi-path observations detected by the two methods are statistically calculated: the results show that the reference function method accounts for 49.91% of the multipath value and the dual statistic method accounts for 53.45%. The results of the two methods are not different obviously. The detection results of the double statistic method are not only more consistent with the changes of the pseudorange multipath, but also the detection results are more robust. Regardless of the stability and completeness of Galileo system signals, it can draw a preliminary conclusion that As far as GALILEO is concerned, the dual statistic method is more reliable for detecting phase multipath interference.

6.3 BDS Test

Testing the Beidou system, the data preprocessing and the acquisition of related parameters are the same as those of the GPS and Galileo, but only two frequencies of data are selected for the BDS to test the performance of the two methods, making the experimental results more convincing. Beidou C06 was selected as the reference satellite to test the C07 observations. The parameters of the reference function method and the statistical threshold function model are calculated. Equations (14) and (15) represent the reference function method's SNR statistical model and threshold model, respectively. The function models of the parameters and statistical thresholds of the double statistic method are obtained, which are respectively (16) and (17). Finally, the corresponding statistics and statistical thresholds of the two methods are calculated.

$$\Delta S_{12} = 5.9704 - 0.6730\theta + 0.0189\theta^2 - 1.5399 \times 10^{-4}\theta^3 \tag{14}$$

$$T = 5.3758 - 0.1256\theta + 0.0020\theta^2 - 1.0670 \times 10^{-5}\theta^3 \tag{15}$$

$$\begin{aligned} S_1^* &= 32.5035 + 0.2259\theta + 0.0028\theta^2 - 4.9447 \times 10^{-5}\theta^3 \\ S_2^* &= 26.5331 + 0.8988\theta - 0.0160\theta^2 - 1.0454 \times 10^{-4}\theta^3 \\ \Delta S_{12}^* &= 5.9704 - 0.6730\theta + 0.0189\theta^2 - 1.5399 \times 10^{-4}\theta^3 \end{aligned} \tag{16}$$

$$\begin{aligned} \sigma_1 &= 2.1942 - 0.0875\theta + 0.0014\theta^2 - 7.1392 \times 10^{-6}\theta^3 \\ \sigma_2 &= -5.6223 + 0.5751\theta - 0.0148\theta^2 + 1.1500 \times 10^{-4}\theta^3 \\ \sigma_{12} &= 1.7606 - 0.0227\theta - 3.5238 \times 10^{-4}\theta^2 + 6.1020 \times 10^{-6}\theta^3 \end{aligned} \tag{17}$$

The calculation results of statistics and thresholds about BDS in a multipath environment are shown in Figs. 10 and 11. The detection results of the two methods are in good agreement with the pseudorange multipath error. Especially, after the 6800 s, the values and fluctuations of the pseudorange multipath are both severe, which becomes larger, and the corresponding statistics also start to oscillate. At the same time, the picture shows that the detection results of both methods show that the phase observations during this period are subject to more multipath interference, and the proportion of the detected phase observations was shown in Table 1. The statistical results show that the ratio of the multipath observations of the reference function method is slightly smaller than the double statistic method. It can conclude that the double statistic method is more sensitive to multipath observations.

Table 1. BDS phase multipath detection comparison

Method	Percentage of observations
Reference function method	27.37%
Double statistic method	28.93%

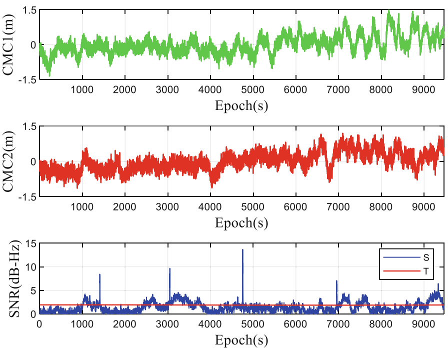

Fig. 10. Reference function detection result

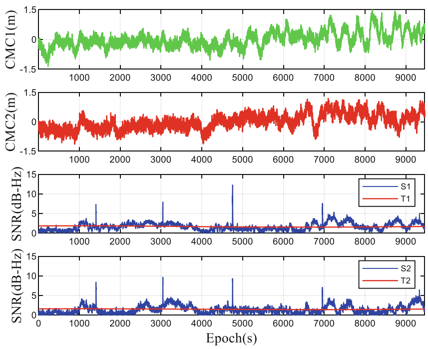

Fig. 11. Double statistic detection result

6.4 Positioning Test

The paper studies the effect of two multipath detection methods on positioning accuracy, and strategies for processing observations containing phase multipath errors are removing. However, the defect of the method is satellite observations to weed out too much, which will change the satellite's geometric structure, and structural changes will reduce the positioning accuracy, or even fail to locate. Thus, from the perspective of the two satellites, this is to ensure that there are enough on the number of satellites and can test the impact of the positioning result. To test the improvement of the positioning accuracy, this experiment is the structure of the artificial multipath environment. First of all, the double-difference combination in a low multipath environment is used to obtain the reference coordinates of the experimental site, since it is an ultra-short baseline, the effect of atmospheric error can eliminate. Then the coordinate is calculated using precise point positioning (PPP) which is in an artificial multipath environment, with reference coordinates to evaluate the precision of coordinate improvement, which takes into account the accuracy of external coincidence making evaluation more persuasive.

It takes BDS as an example to analyze the improvement of positioning accuracy by the phase multipath detection method. Due to the serious multipath of the data acquisition site, the PPP positioning result can only reach the decimeter level. In Fig. 12, the improvement of the precision of the coordinates of the direction of E and N is very weak but can be seen clearly in the U direction accuracy, which is improved obviously. The statistical results of RMS values of all directions are showed Table 2, After the correction of the two methods, RMS values obviously decrease, and the results of the two kinds of method display improvement of its internal precision. Then it is compared with the reference coordinates to check the accuracy of external coincidence. In Table 3, through comparison, it is an opinion that both the reference function method and the double statistic method can significantly improve the positioning accuracy, especially in the direction of U. This also proves the feasibility of using C/N0 to study the variation law of phase multipath. However, the defect of this method is that it cannot be used when the number of observation satellites is small. Therefore, a more reasonable method should start from the stochastic model and change the weight of multipath observation. Relevant studies can be referred to as the literature [14]. Certainly, the positioning accuracy of the multi-systems combination is also preliminary tested The positioning accuracy has also been significantly improved, but it will not be listed separately given the limited space available.

Table 2. Comparison of positioning accuracy (precision of inner coincidence)

Type of data	E	N	U
Raw data	0.3618	0.6072	0.4214
Reference function method correction	0.1393	0.1333	0.2930
Double statistic method correction	0.1281	0.1826	0.2838

Table 3. Comparison of accuracy based on reference coordinates (External accord accuracy)

Type of data	E	N	U
Raw data	−0.7273	0.5846	−4.0649
Reference function method correction	0.4876	0.5118	−1.7884
Double statistic method correction	0.6266	0.5316	−1.4964

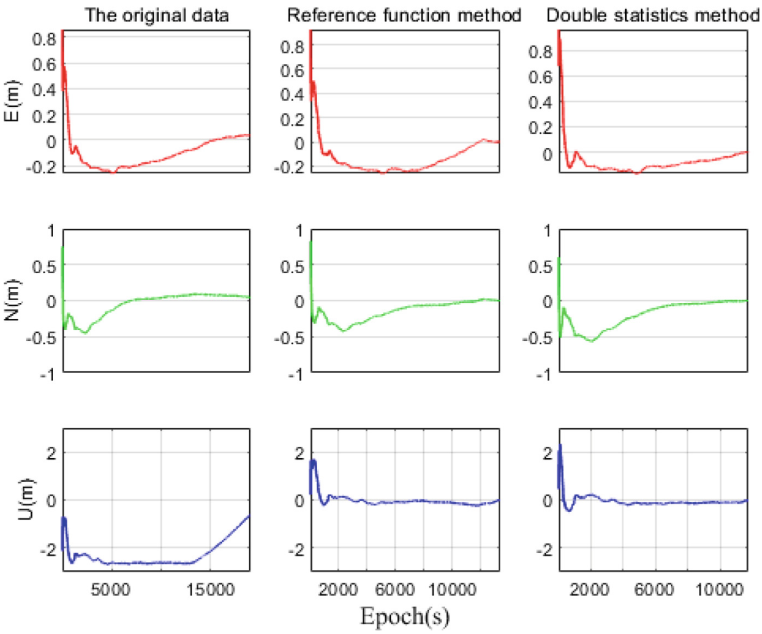

Fig. 12. Precise Point Positioning result

7 Conclusion

Multipath effects in complex environments have been the main source of error that restricts high-precision positioning. Based on the relationship between SNR and multipath, this paper explores two multipath detection methods under adverse observation conditions about the reliability of detection of GPS, GALILEO, and BDS. It was found that different methods have small differences in the detection results of different systems. From the experimental results, for the GPS, Galileo, and BDS, both methods can reliably detect multipath, and the capability of the double statistics method are more robust. The BDS and multi-GNSS are used to test the feasibility of studying phase multipath through the C/N0. The experimental results show that the two methods can improve the positioning accuracy after correction. Besides, the reference function method and double statistics method can not only detect multipath errors (including pseudorange multipath and phase multipath) but also detect other unmodeled errors. Both methods can be applied to dual-frequency, triple-frequency or even multi-frequency, and the detection results of the double statistic method are more robust, the reference function method is simpler from the method point of view, so the users can choose the appropriate method according to different scenarios. Multipath detection based on SNR can be used as a new method of data quality control, and it can be applied to the navigation and high-precision positioning research in dynamic and real-time fields and a variety of complex environments.

Acknowledgments. This work is supported by the National Natural Science Foundation of China (No. 2016YFB0501803).

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