Method of Quality Assessment for BOC Navigation Signal Based on Multi-correlation Receiver

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Abstract. The integrity of navigation signal can be reflected on the correlation curve, so the quality of the signal can be evaluated by analyzing the correlation curve of navigation signal. Aiming at the binary offset carrier (BOC) modulation used in the navigation signal, and Taking BOC (1,1) as an example, the acquisition and tracking algorithm of the BOC signal is given first in this paper. Then the software receiver based on the multi-correlator is designed, and the performance of the correlation curve is analyzed from the aspects of pseudo-range difference value, multiple correlation value difference and multiple correlation value symmetry. The simulation results show that the BOC signal synchronization method proposed in this paper can be effectively captured and tracked, and the output results of the multi-correlator can accurately reflect the quality performance of the navigation signal, so it is suitable for signal quality assessment of BOC receiver.

Keywords: BOC navigation signal · Quality assessment · Multi-correlation receiver

1 Introduction

The basic task of navigation is to determine the position of the carrier, and guide the users from the current location to the destination, according to the given time and route. With the rapid development of the Global Navigation Satellite System (GNSS), the military, aerospace, transportation, surveying and mapping, seismic monitoring and other industries have a growing need for high-precision positioning and navigation. However, measurement errors caused by satellite clock errors, satellite ephemeris errors, ionospheric delay [1], tropospheric delays, and multipath effects have seriously affected the measurement accuracy of the GNSS. Among them, the first four types of errors are systematic errors, which can be eliminated by differential or modeling methods. While multipath errors are difficult to eliminate through differential technology due to their time-varying and environment-dependent characteristics, and become the most important factor affecting high-precision ranging.

Multipath effect means that in addition to the direct navigation signal, the receiver also receives various other indirect signals at the same time. These indirect signals are

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called multipath signals. Multipath signals will distort the correlation function between the synthesized signal (direct signal plus multipath signal) received by the receiver and the local reference signal generated by the receiver. What's more, multipath signals will also cause distortion of the received signal's synthesized carrier phase. Errors are introduced in the measured values of pseudo-range and carrier phase (different signals transmitted by different satellites have different values), resulting in positioning, speed fixation, and timing errors. In severe cases, it can also cause code phase lock-lose, carrier phase lock-lose, and missing the satellite signal. Therefore, suppressing multipath errors effectively is a key technology to improve the navigation and positioning accuracy of the global navigation satellite system.

Since the spread spectrum modulated signal used in the navigation system has good autocorrelation, and its lead-lag correlation curve is symmetrical, it is possible to consider setting up multiple correlators in the receiver and use the correlation curve to monitor whether multipath or distortion exists in the navigation signal. In this paper, the new system BOC modulation signal is studied. Taking BOC (1,1) as an example, a suitable synchronization receiving algorithm is proposed by analyzing its frequency spectrum and autocorrelation function. Then the quality of navigation signals will be monitored and evaluated by setting multiple correlators, and performing pseudo-range difference detection, correlation value difference detection, symmetric ratio detection and other methods.

2 Signal Model and Synchronization Method

2.1 BOC Signal Model

The BOC signal adds square wave subcarrier modulation on the basis of pseudo code modulation. As a result, the original BPSK spectrum is split into two symmetrical spectrums about the carrier frequency, and there is no energy distribution on the center carrier frequency. This split-spectrum feature allows it to share the frequency band with the original signal on the satellite system. In addition, the BOC modulated signal has a sharper correlation peak than the original BPSK signal, so it has better positioning accuracy, higher anti-multipath and anti-narrowband interference capabilities. The BOC modulated navigation signal can be expressed as:

$$s(t) = e^{-i\theta} \sum_{k} a_k \mu_{nT}(t - knT - t_0) c_T(t - t_0) \tag{1}$$

In the formula, a_k is the spreading code after data modulation with unit amplitude. μ_{nT} is the spreading symbol (pseudo code symbol), the length of chips is nT, where n is a positive integer, representing the ratio of a pseudo-code chip length to half the subcarrier period, also known as the BOC spreading ratio [1]. $c_T(t)$ is the subcarrier, which is a square wave with a period of $2T$. Usually $c_T(t) = \mathrm{sign}(\sin(2\pi f_s t))$ or $c_T(t) = \mathrm{sign}(\cos(2\pi f_s t))$, where $f_s = 1/2T$ is the subcarrier frequency, and $\mathrm{sign}(\bullet)$ is the sign function. θ and t_0 are the phase and time offsets relative to a reference respectively. The modulation process can be expressed as Fig. 1:

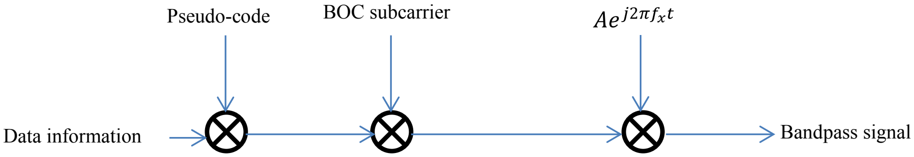

Fig. 1. The process of the BOC modulation

In satellite navigation systems, the BOC modulated signal is usually abbreviated as $BOC(\alpha, \beta)$, where α represents the subcarrier frequency $\alpha \times 1.023\,\text{MHz}$ and β represents the pseudo code rate $\beta \times 1.023\,\text{MHz}$, besides $n = 2\alpha/\beta$.

2.2 BOC Signal Synchronization Method

Taking BOC (1,1) signal as an example, its acquisition method can use ASPeCT (autocorrelation side-peak cancellation technique) algorithm, which is suitable for BOC (n,n) signal acquisition. The specific process is as follows: First, the input IF signal Is multiplied by the local carrier of the in-phase and orthogonal branch to carry out carrier stripping. Then each branch signal is divided into two groups. One group is correlated with the spreading code modulated by the subcarrier, and the other group performs correlation operations with spreading codes of unmodulated subcarrier [2]. Finally the calculation results are squared, and then the processing results of the four branches are combined in a certain manner. The process is shown in Fig. 2.

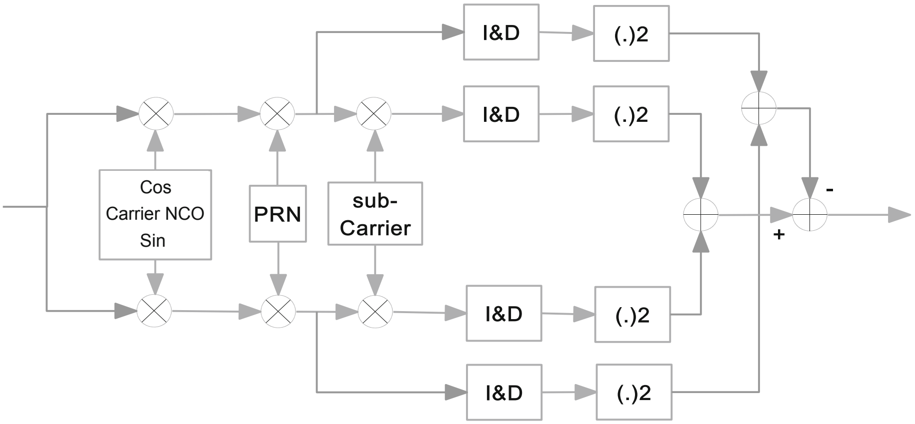

Fig. 2. Block diagram of ASPeCT algorithm

BOC signal includes subcarrier modulation and pseudo-code modulation, so it is proposed to use three-loop tracking algorithm. The main idea of the three-loop tracking algorithm is: the autocorrelation of the BOC signal is obtained by multiplying the autocorrelation result of the pseudo code and the autocorrelation result of the subcarrier. Then the pseudo code and subcarrier can be tracked separately to obtain the phase of the pseudo code rough estimation and precise estimation [3]. Finally combining the phase measurement values of the code tracking loop and the subcarrier tracking loop can get a more accurate code phase tracking result. The specific process is shown in Fig. 3:

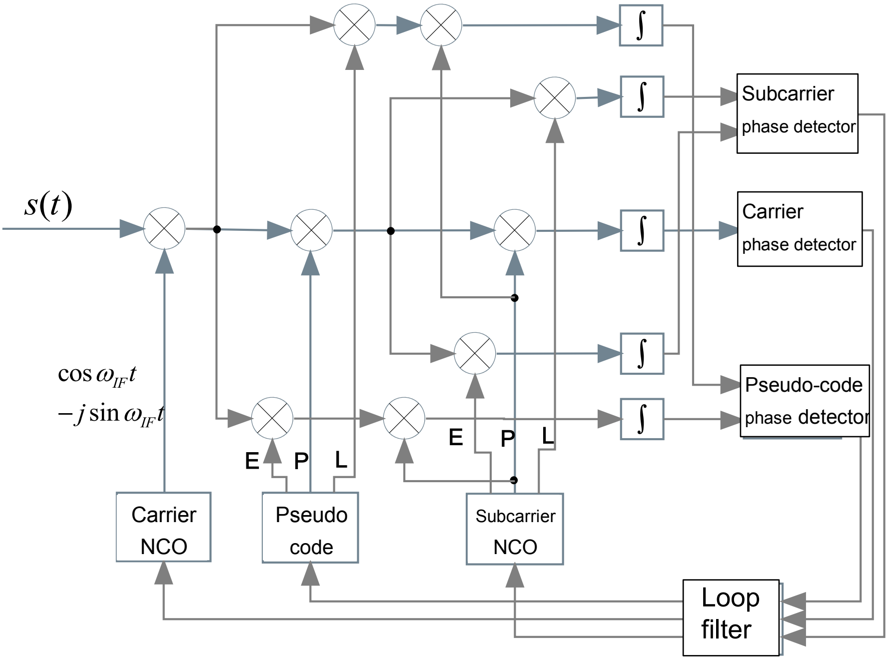

Fig. 3. Block diagram of the dual-loop tracking algorithm

3 Multiple Correlators Detection Method

3.1 Pseudo-range Difference Detection Method

The pseudo-range from the receiver to the satellite i is defined as follows:

$$\rho_i = c[T_R(n) - T_{Ti}(n)] \tag{2}$$

In the formula, c = 299792458 m/s is the speed of light in the vacuum. $T_R(n)$ represents the receiving time corresponding to the n epoch of the GNSS receiver clock. $T_{Ti}(n)$ represents the launch time based on the satellite i clock.

Under ideal conditions, the pseudo-range measurement values obtained by the code tracking loop at different correlation intervals are equal, and the difference value should be zero. Once the correlation function is deformed, the difference between the pseudo-range measurements will no longer be zero. If the receiver is configured with multiple channels with different correlation intervals, it can be judged whether the navigation signal is abnormal by observing the difference between the pseudo-range measurement values of each channel. The measurement values are as follows:

$$\beta_\rho = \max \begin{bmatrix} \frac{\Delta\tau_a(d_1,d_2)-\Delta\tau_{nom}(d_1,d_2)}{MDE_{d_1,d_2}} \\ \frac{\Delta\tau_a(d_1,d_3)-\Delta\tau_{nom}(d_1,d_3)}{MDE_{d_1,d_3}} \\ \vdots \\ \frac{\Delta\tau_a(d_1,d_n)-\Delta\tau_{nom}(d_1,d_n)}{MDE_{d_1,d_n}} \end{bmatrix} \tag{3}$$

As long as this metric value is greater than 1, it is considered that the navigation signal is abnormal. The difference of the pseudo-range measurement values between different correlation intervals in the above formula is expressed as:

$$\Delta\tau\left(d_i, d_j\right) = \tau(d_i) - \tau\left(d_j\right) \tag{4}$$

$$\tau(d) = \arg[R\left(\tau + \frac{d}{2}\right) - R\left(\tau - \frac{d}{2}\right)] = 0 \tag{5}$$

Among them, $q = a$ or norm. a means abnormal signal, and norm means ideal signal. $R(d)$ represents correlation value. d_i represents different correlation intervals. $MDE\left(d_i, d_j\right)$ is the minimum detection error threshold corresponding to the correlation interval d_i and d_j.

This method requires each channel to track the satellite independently, and each channel is configured with a correlation interval. Therefore, a large number of channels are needed to obtain the pseudo-range of the same satellite, which leads to a complex system and higher requirements for monitoring receivers. In addition, it can be found that this method cannot identify the flat-top effect of the correlation function from Eqs. (4) and (5).

3.2 Correlation Value Difference Detection Method

Generally speaking, the pseudo-range value is obtained based on the output value (correlation value) of the correlator. Therefore, monitoring can also be achieved by using relevant values. The use of correlation values for detection also requires multiple correlation intervals, but only one lead-lag code tracking loop is required to track the correlation peak. While other lead-lag correlators with different correlation intervals do not participate in loop tracking and output correlation values directly.

$$\gamma_\Delta = \max\begin{bmatrix} \frac{(\Delta_{a,1}-\Delta_{a,ref})-(\Delta_{nom,1}-\Delta_{nom,ref})}{MDE_{1,ref}} \\ \frac{(\Delta_{a,2}-\Delta_{a,ref})-(\Delta_{nom,2}-\Delta_{nom,ref})}{MDE_{2,ref}} \\ \vdots \\ \frac{(\Delta_{a,n-1}-\Delta_{a,ref})-(\Delta_{nom,n-1}-\Delta_{nom,ref})}{MDE_{n-1,ref}} \end{bmatrix} \tag{6}$$

$$\Delta_m = R\left[\tau_{ref} - \frac{d_m}{2}\right] - R\left[\tau_{ref} + \frac{d_m}{2}\right] \tag{7}$$

$$\tau_{ref} = \arg\{R\left(\tau - \frac{d_{ref}}{2}\right) - R\left(\tau + \frac{d_{ref}}{2}\right) = 0\} \tag{8}$$

In the formula, there are n correlation pairs (one of them is used for tracking). τ_{ref} is the maximum correlation peak position estimated by the tracking correlation pair. A more straightforward description is that $R\left[\tau_{ref} \pm \frac{d_m}{2}\right]$ is the correlation value of the relative output with a correlation interval of d_m, which can be directly obtained.

It is worth noting that $\Delta_{a,ref} \neq 0, \Delta_{nom,ref} \neq 0$ for non-ideal signals. It is guessed that the above expression is complicated to ensure the accuracy of the expression. When the phase tracking is locked, the detection amount can also be expressed by the real part of the normalized correlation output:

$$\Delta_m = \frac{I_{early,m} - I_{late,m}}{2I_{prompt}} \tag{9}$$

In the above formula, 2 is the phase discrimination gain, which needs to be changed for the BOC signal.

3.3 Symmetry Ratio Detection Method

The ideal correlation function is not only symmetrical, but also the slope of the curve is definite. The deformation of the correlation function will change the slope of the curve. Therefore, observing the slope of each point of the correlation curve can detect signal abnormalities [4]. This method uses the ratio of the leading and lagging branch measured values to the instant branch measured values, which is divided into bilateral detection and unilateral detection. The metric for bilateral detection is:

$$R_{double} = \frac{I_{early} + I_{late}}{2I_{prompt}} \tag{10}$$

The metric for unilateral detection is:

$$\begin{cases} R_{single,early} = \frac{I_{early}}{I_{prompt}} \\ R_{single,late} = \frac{I_{late}}{I_{prompt}} \end{cases} \tag{11}$$

In the above formula, there is only one instant branch, and there are multiple lead-lag correlators. For a receiver channel containing n lead-lag correlator pairs, the metric can be expressed as:

$$\gamma_R = \max \begin{bmatrix} \frac{R_{a,1}-R_{nom,1}}{MDE_{R_1}} \\ \frac{R_{a,2}-R_{nom,2}}{MDE_{R_2}} \\ \vdots \\ \frac{R_{a,n}-R_{nom,n}}{MDE_{R_n}} \end{bmatrix} \tag{12}$$

Since some signal anomalies only affect one side of the correlation curve, unilateral detection is helpful to improve the sensitivity to such distortions. The composition of the formula is flexible. If only the bilateral or one-sided unilateral detection is performed, substitute the corresponding detection amount into the formula. The bilateral and two-sided unilateral detection can also be performed at the same time [5].

4 Performance Simulation and Analysis

4.1 Signal Synchronization Performance

The BOC (1,1) signal is first generated in the simulation. The carrier intermediate frequency $F_c = 1.023\,\text{MHz}$, and the carrier Doppler $F_D = 2500KHz$. The rate of pseudo code is $1.023Mcps$. In addition, the number of bits of the signal becomes longer due to BOC (1,1) modulation. In order to reduce the calculation time, we set the sampling rate of the pseudo code to $F_s = 19.437\,\text{MHz}$; carrier ratio $C_{N0} = 70$; signal-to-noise ratio $SNR = C_{N0} - 10 * \lg(F_s) = 62.4$.

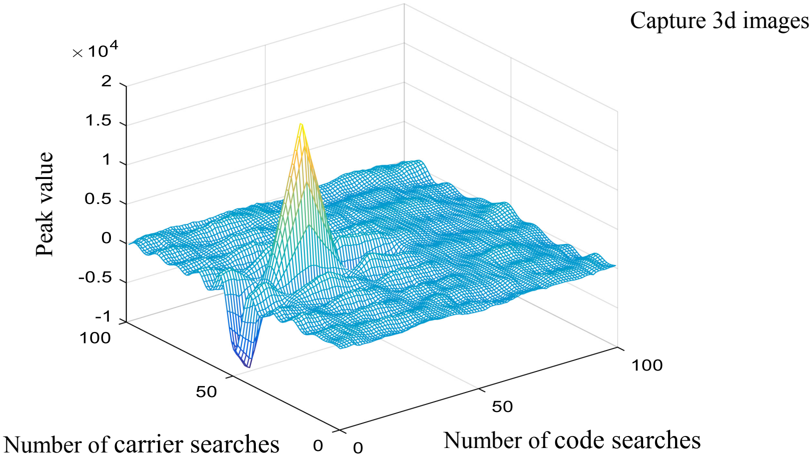

Fig. 4. BOC signal acquisition

The signal acquisition result is shown in Fig. 4. In the figure, the C/A code shifted 53 chips to the right, and the carrier is shifted by 2.5 kHz. There is a peak at x = 51 and y = 25.

The following is the curve of tracking the pilot signal when the satellite number is 18 (Fig. 5).

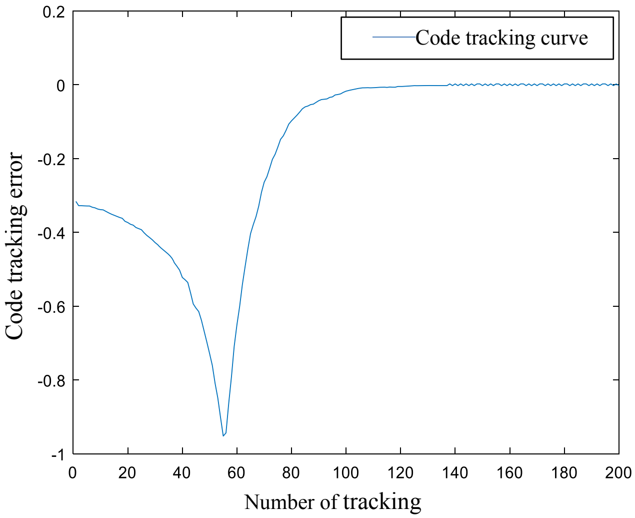

Fig. 5. BOC signal code tracking curve

We can see that after about 110 cycles, the C/A code was successfully tracked (Fig. 6).

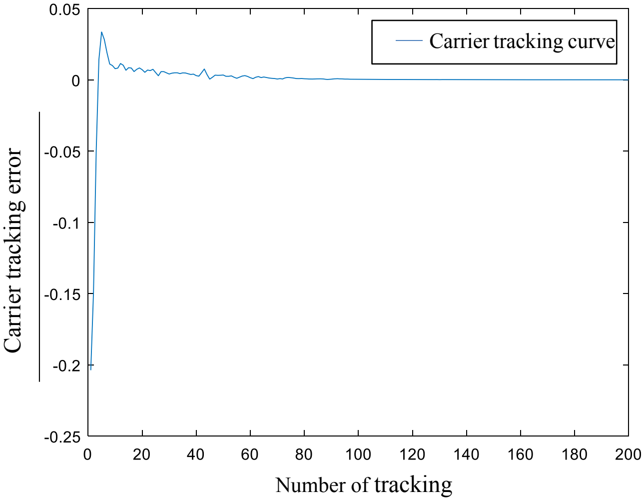

Fig. 6. BOC signal carrier tracking curve

It can be seen that after approximately 70 cycles, the carrier was successfully tracked.

4.2 Performance of Pseudo-range Difference Detection

Since the calculation of the pseudo-range requires real and reliable GNSS data, here we use the actual collected GNSS signals for simulation. The Fig. 7 is the satellite captured. We can see that the signals of the 03, 06, 09, 15, 18, 21, 22, and 26 satellites have been captured.

We take the 18th satellite signal for pseudo-range simulation. First set up four tracking channels, and the intervals (lead minus lag) of the four tracking channels are respectively 0.1 chip, 0.06 chip, 0.07 chip, and 0.08 chips. The tracking result obtained by each tracking channel is used to calculate the pseudo-range.

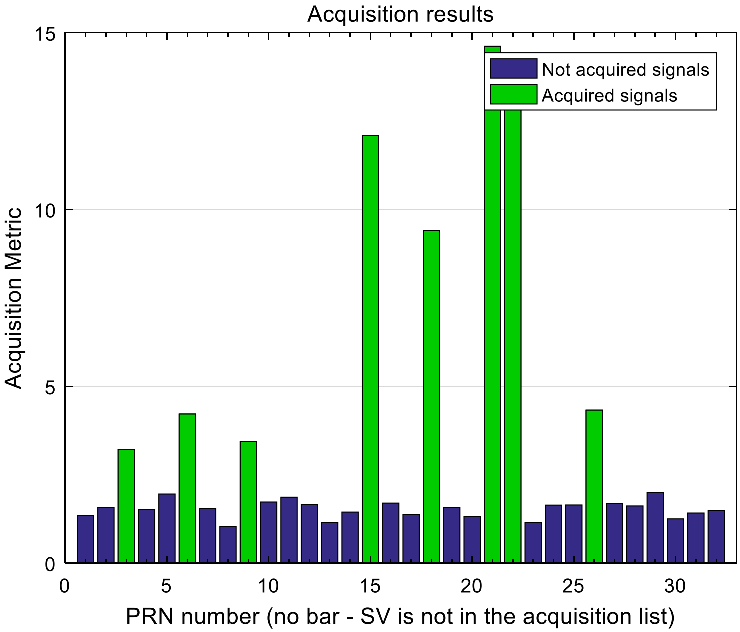

Fig. 7. Satellite capture image

Then we got the signal propagation time T of each channel, the values of T are 69.338 ms, 69.339 ms, 69.338 ms, 69.338 ms respectively. The pseudo-range values of the four channels calculated from $\rho = T \times c$ are 20787143 m, 20787190 m, 20787143 m and 20787143 m. As shown in Fig. 8.

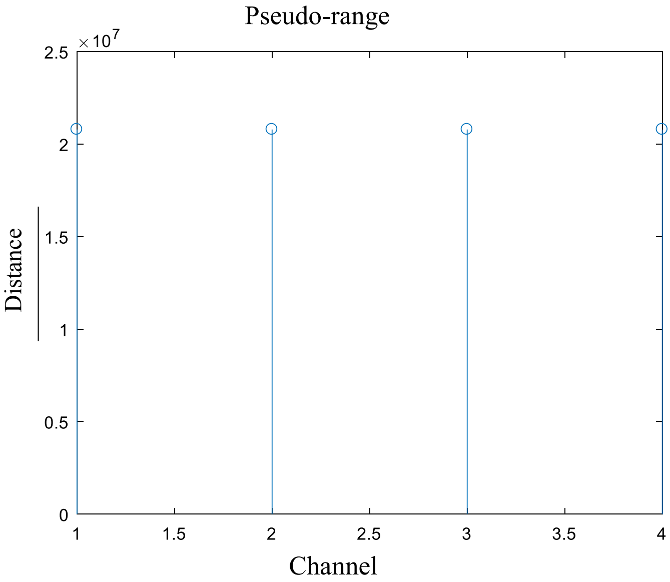

Fig. 8. Pseudo-range difference image

From Fig. 8, we can see that the pseudo-ranges calculated by tracking channels with different tracking intervals is slightly different, among which the pseudo-ranges measured by the middle second channel is the largest. We can see that the tracking channels are different, and the difference is not very significant. The difference here mainly comes from satellite clock errors, satellite ephemeris errors, channel noise interference and so on [6]. Under ideal conditions, the pseudo-range measurement values obtained by the code tracking loop at different correlation intervals are equal, and the difference should be zero. Once the correlation function is deformed, the difference between the pseudo-range measurements will no longer be zero.

4.3 Performance of Multi-correlation Value Difference Detection

We used correlation values to detect, and 21 correlation intervals were configured with only one tracking channel. Among them, with the instantaneous code as the center, there are 10 related channels on the left and right. Adjacent channels are separated by 1/19 chips. The following curve is obtained by accumulating the values of each channel.

Among them, the formula for calculating the correlation value of each relevant channel is as follows (only take the most advanced channel as an example): calculate the cumulative sum of the I and Q branches respectively, and then take the square root of the arithmetic sum of the two.

$$I\_E(t) = \sum earlyCode(t) \times iBasebandSignal(t); \tag{13}$$

$$Q\_E(t) = \sum earlyCode(t) \times qBasebandSignal(t); \tag{14}$$

$$y = \sqrt{(I\_E \times I\_E + Q\_E \times Q\_E)}; \tag{15}$$

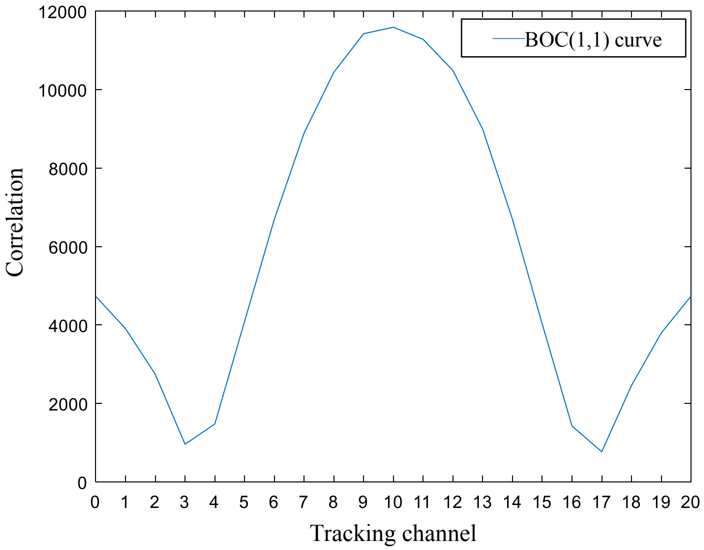

Fig. 9. BOC signal correlation curve

As shown in the Fig. 9, the curve has a peak at x = 10. Since x = 10 is the location of the instant code channel, the peak appears here. It can be found that the correlation curve is similar to the BOC (1,1) signal correlation curve. From the simulation results, we can see that the sharp part of the curve in the middle is not straight, but slightly jittered, and the jitter becomes more serious the higher the top is, then analysis shows that the signal is abnormal. However, compared with BPSK signal, its curve jitter is smaller, which can also reflect the benign nature of the BOC signal.

4.4 Performance of Symmetry Ratio Detection

The slope of each point of the sharp part of the correlation curve was simulated with MATLAB, as shown in the following Fig. 10:

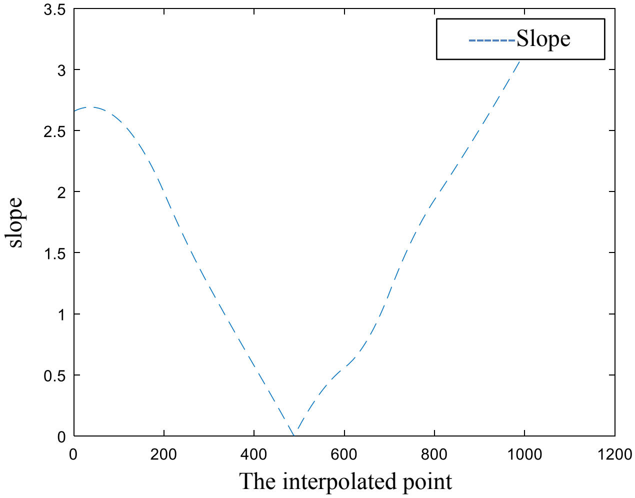

Fig. 10. BOC signal slope curve

First perform spline interpolation on the relevant curve and obtain 1000 points, then the values of the slope obtained after a differential of each point. The ideal correlation function is not only symmetrical, but also the slope of the curve is determined. The deformation of the correlation function will change the slope of the curve. Therefore, by observing the slope of each point of the correlation curve, we can see that the slope is changing. It can be concluded that the correlation curve is not a straight line but may be a multiple curve, so the signal is abnormal.

5 Conclusion

This paper proposes a navigation signal monitoring method based on multi-correlator for the GNSS navigation signal modulated by BOC. Taking BOC (1,1) modulation signal as an example, the paper first studies the acquisition and tracking algorithm of

BOC signal, then analyzes the pseudo-range difference performance of each tracking channel under different correlation intervals based on multiple tracking channels. What's more, this paper analyzes the multi-correlation value difference and the symmetry performance of the correlation curve. The simulation results show that the BOC synchronization method proposed in the paper can capture and track effectively. The signal monitoring method based on multi-correlator can effectively detect the distortion and interference of the navigation signal, thereby providing a reliable method for detecting the integrity of the navigation signal.

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