Performance Analysis of Multipath Mitigation Using Different Anti-multipath Techniques in BPSK and BOC Modulated Signals

Xiyan Sun[1,2], Shaojie Song[1,2](✉), and Yuanfa Ji[1,2]

[1] Guanxi Key Laboratory of Precision Navigation Technology and Application,
Guilin University of Electronic Technology, Guilin 541004, China
ssjl816977054@163.com
[2] National & Local Joint Engineering Research Center of Satellite Navigation
and Location Service, Guilin 541004, China

Abstract. Multipath is a major source of positioning error in high precision navigation applications. Narrow correlator method and Gating signal correlator method are two effective methods for BPSK modulation signals multipath mitigation. In this paper, the mathematic model of multipath error are first established, and then multipath mitigation performance of the BPSK signal and BOC modulation signal are analyzed and simulated based on the narrow correlator method in a comparative way. The simulation results show that BOC signal is better than BPSK signal as for multipath mitigation performance. The consistency between narrow correlator and gating signal correlator method is deduced and proven theoretically. And it is concluded that the BOC code tracking loop phase discriminator function has ambiguity using the gating signal multipath mitigation method, so the gating signal multipath mitigation method does not work for BOC signal tracking code loop phase discriminator. Finally, the correctness of theoretical derivation is verified through simulation.

Keywords: Binary offset carrier · Gating signal · Narrow correlator · Multipath mitigation

1 Introduction

Multipath error is one of the most dominant error sources of high precision GPS positioning [1, 2]. Because multipath errors are greatly affected by the environment, and there is no correlation in time and space, so it is difficult to eliminate them by traditional differential methods. Study on multipath has always been a hot spot in the satellite navigation community. The relatively early and effective method for BPSK signal multipath mitigation is NovAtel's narrow correlator technology (NC) [3, 4]. With the implementation of the GPS modernization program and the successive emergence of Galileo and COMPASS systems, a new type of binary offset carrier (BOC) modulation signal [5, 6] has been adopted widely. The BOC signal is generated after the information code is multiplied by the pseudo-code spread spectrum, and then multiplied by a square wave sub-carrier with a higher rate than the pseudo-code rate. In this way, the original spectrum is split into two parts. Due to the splitting of the

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spectrum, the overcrowded navigation frequency band can also meet the compatibility of navigation systems to a certain extent, and avoid interference between navigation systems. In addition, the BOC signal has a sharper autocorrelation peak than the BPSK signal (as shown in Fig. 1). Therefore, the BOC signal has better ranging performance and multipath mitigation [7]. The multipath mitigation method used for the BPSK signal is based on the unimodality of the autocorrelation function of the BPSK signal, such as the narrow correlator method and the gating signal correlator method. However, the autocorrelation function of the BOC signal has multiple peaks (as shown in Fig. 1). Whether these multipath mitigation methods can be adapted to the BOC signal remains to be further demonstrated.

Aiming at the above problems, this paper comparatively analyses the multipath mitigation performance of on BPSK and BOC modulation signal using the narrow correlator method. The consistency of the gate signal correlator and narrow correlator method is derived and proved theoretically. The result shows that BOC signal is superior to BPSK signal in multipath mitigation performance by narrow correlation method. The structure of this article is as follows: Sect. 2 introduces the multipath error model of GPS receiver BPSK and BOC signals, and uses the method of formula derivation to visually show the receiver pseudo-range error and influence caused by multipath signals. The performance of multipath suppression for BPSK and BOC signals using two multipath suppression methods such as narrow correlation and gate function be tested in Sect. 3. Section 4 gives a conclusion of this paper.

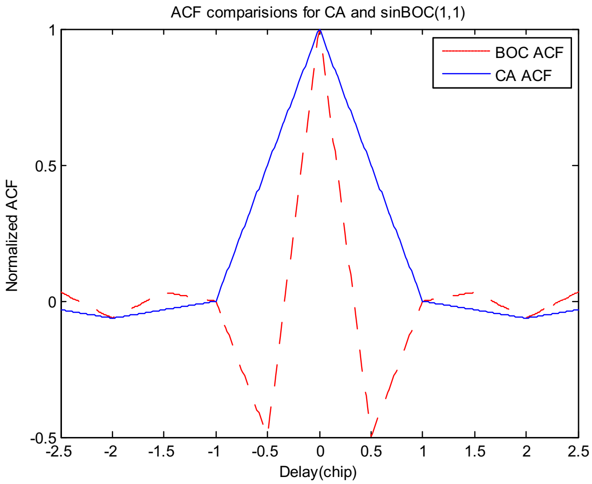

Fig. 1. Comparison of autocorrelation function of the BOC and BPSK signal

2 Multipath Error Model

2.1 Multipath Signal Model

The GPS receiver receives the superimposed signal of the satellite direct signal and the multipath signal reflected by the objects around the receiver, so the BPSK intermediate frequency signal [8] received by the receiver can be expressed as:

$$s(t) = \sum_{i=0}^{M} \alpha_i A d(t) c(t - \tau_i) \cos[w_0 t + \phi_i(t)] \tag{1}$$

Where $i = 0$ is the satellite direct signal, remaining M–1 signals are multipath signals, A is the carrier amplitude, the A value is assigned 1 in order to simplify the analysis process, α_i is the ratio of multipath to direct signal amplitude (attenuation coefficient MDR), α_0 corresponds to direct signal, $d(t)$ is the navigation message, $c(t - \tau_i)$ are the GPS pseudo-random codes with different delays, w_0 is the intermediate frequency of the satellite signal, this paper assumes that the direct signal and the multipath signal have the same frequency, $\phi_i(t)$ is the phase of the i-th signal.

The BOC IF signal received by the receiver can be expressed as:

$$s(t) = \sum_{i=0}^{M} \alpha_i d(t) sc(t) c(t - \tau_i) \cos[w_0 t + \phi_i(t)] \tag{2}$$

Where $sc(t) = sign[\sin(2\pi f_{sc} t)]$ represents sine BOC modulation signal, $sc(t) = sign[\cos(2\pi f_{sc} t)]$ represents cosine BOC modulation signal.

Assuming that the local carrier correctly tracks the frequency of the received signal, the locally generated in-phase signal and quadrature signal can be expressed as:

$$y_i(t) = c(t - \hat{\tau}_0) cos[w_0 t + \hat{\phi}_0] \tag{3}$$

$$y_q(t) = c(t - \hat{\tau}_0) sin[w_0 t + \hat{\phi}_0] \tag{4}$$

Assuming that during the integration process, the navigation message remains unchanged (that is, the meaning of the navigation message can be ignored), that is $d(t) = 1$, the correlation between the received signal and the local signal is

$$\begin{aligned} IP(\tau) &= \frac{1}{T}\int_0^T s(t) y_i(t - \tau) dt \\ &= \frac{1}{T}\int_0^T \{\sum_{i=0}^{M} \alpha_i c(t - \tau_i) cos[w_0 t + \phi_i(t)]\}\{c(t - \hat{\tau}_0) cos[w_0 t + \hat{\phi}_0(t)]\} dt \\ &\approx \sum_{i=0}^{M} \alpha_i R(\hat{\tau}_0 - \tau_i) \frac{1}{2}\{\cos[2 w_0 t + \phi_i + \hat{\phi}_0] + cos(\phi_i - \hat{\phi}_0)\} \end{aligned} \tag{5}$$

Filtering out the high frequency part in Eq. 5 can be expressed as

$$IP(\tau) = \sum_{i=0}^{M} 0.5\alpha_i R(\hat{\tau}_0 - \tau_i) cos(\phi_i - \hat{\phi}_0) \tag{6}$$

Where $\hat{\tau}_0$ is the delay estimation of the direct signal, $\hat{\phi}_0$ is the carrier phase estimation of the direct signal.

2.2 Narrow Correlator Method

The traditional GPS receiver uses three correlators (Prompt, Early and Late) and correlation techniques to capture and track PRN codes, and thus the time delay estimation of direct signal is $\hat{\tau}_0$. Then, $\hat{\tau}_0$ is tracked by the delay lock loop (DLL) to measure the pseudo-range from the satellite to the receiver. Narrow correlator technology [9] is widely used in navigation receivers as the earlier effective multipath mitigation technology. It improves the anti-multipath capability of code tracking ring by reducing the spacing between early correlator and late correlator.

The correlation function of prompt(P), early(E) and late(L) can be respectively impressed as:

$$IP(\tau) = \sum_{i=0}^{M} \frac{\alpha_i}{2} R(\hat{\tau}_0 - \tau_i) cos(\phi_i - \hat{\phi}_0) \tag{7}$$

$$IE(\tau) = \sum_{i=0}^{M} \frac{\alpha_i}{2} R(\hat{\tau}_0 - \tau_i + \frac{d}{2}) cos(\phi_i - \hat{\phi}_0) \tag{8}$$

$$IL(\tau) = \sum_{i=0}^{M} \frac{\alpha_i}{2} R(\hat{\tau}_0 - \tau_i - \frac{d}{2}) cos(\phi_i - \hat{\phi}_0) \tag{9}$$

In the traditional receiver, the correlator spacing d is 1Tc generally. However, d is less than 1Tc in the narrow correlator technique. Using the Eq. 8 and Eq. 9, the discriminator output expression of narrow correlator technique can be expressed as:

$$D_{narrow} = IE - IL \tag{10}$$

Where the spacing d between the early and late correlator is less than 1Tc.Figure 2 shows the phase discriminator output of BPSK signal and BOC(1,1) signal when the narrow correlator interval d = 0.1Tc.

Since the bandwidth of the actual receiver channel is limited, the peak value of the correlation function will not only become smooth, but also a position shift may occur, under the combined influence of the multipath signal and the limited bandwidth. When d decreases below the inverse of the bandwidth of the receiving channel, the tracking error will tend to be a constant. Therefore, due to the limitation of the receiver channel bandwidth, continuously reducing the correlation spacing d cannot reduce the multipath error indefinitely.

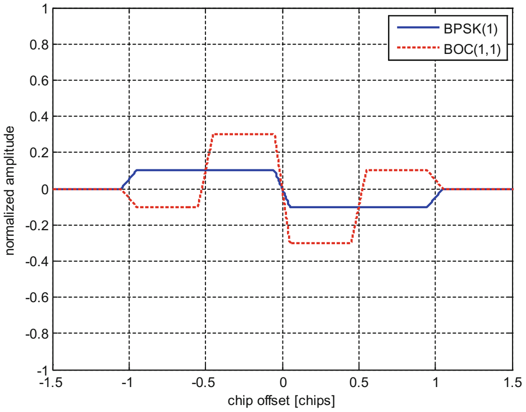

Fig. 2. Phase discriminator output of BPSK and BOC(1,1)

2.3 Gating Signal Correlator Method

In addition to the narrow correlator method, the gating signal correlator method [9, 10] is a signal correlation calculation method similar to the narrow correlator. The locally generated code of the gating signal correlator method is no longer the recurring code generated by the traditional receiver, but one or more gate-like signals, called Gating Signals. There are many ways to construct the gating signal structure, and one of them is shown in and Fig. 10 [9, 10]. The mathematical expression is

$$w(t-\tau)=\sum_{k} c_k g(t-kT_c-\tau) \tag{11}$$

Where c_k is the gating signal amplitude. It can be seen from the above expression that the period of the gating signal is the same as the period of the CA code.

The receiver signal processing process of the gating signal correlator method is as follows. The in-phase(I) branch and quadrature(Q) branch signals of the received BOC and BPSK signal can be expressed as, respectively

$$s_{i\_BOC}=\sum_{i=0}^{M}\alpha_i d(t)sc(t)c(t-\tau_i)cos[w_0t+\phi_i(t)] \tag{12}$$

$$s_{q\_BOC}=\sum_{i=0}^{M}\alpha_i d(t)sc(t)c(t-\tau_i)sin[w_0t+\phi_i(t)] \tag{13}$$

$$s_{i\_BPSK}=\sum_{i=0}^{M}\alpha_i d(t)c(t-\tau_i)\cos[w_0t+\phi_i(t)] \tag{14}$$

$$s_{q\_BPSK} = \sum_{i=0}^{M} \alpha_i d(t)c(t-\tau_i)sin[w_0 t + \phi_i(t)] \tag{15}$$

The symbols in Eq. 12 to Eq. 15 have the same meaning as in Eq. 1. In order to facilitate the derivation of the formula, the multipath signal is not considered. The received signal after the phase changes through rotation can be expressed as:

$$\begin{aligned} \begin{bmatrix} y_i(t) \\ y_q(t) \end{bmatrix} &= \begin{bmatrix} \cos(\hat{w}_0 t + \hat{\phi}_0) & sin(\hat{w}_0 t + \hat{\phi}_0) \\ -sin(\hat{w}_0 t + \hat{\phi}_0) & \cos(\hat{w}_0 t + \hat{\phi}_0) \end{bmatrix} \begin{bmatrix} s_i(t) \\ s_q(t) \end{bmatrix} \\ &= \begin{bmatrix} \cos[(w_0 - \hat{w}_0)t + (\phi_0 - \hat{\phi}_0)] \\ sin[(w_0 - \hat{w}_0)t + (\phi_0 - \hat{\phi}_0)] \end{bmatrix} \begin{bmatrix} s_i(t) \\ s_q(t) \end{bmatrix} \end{aligned} \tag{16}$$

Where $\hat{w}_0$ is the frequency estimation, $\hat{\phi}_0$ is the phase estimation. Assuming that the carrier frequency has been correctly tracked by the carrier loop, that is $w_0 - \hat{w}_0 = 0$.Let $\phi_0 - \hat{\phi}_0 = \phi_e$, $\tau_0 = 0$, $d(t) = 1$, Eq. 16 can be re-expressed as:

$$\begin{bmatrix} y_i(t) \\ y_q(t) \end{bmatrix} = \alpha_0 sc(t)c(t) \begin{bmatrix} \cos(\phi_e) \\ sin(\phi_e) \end{bmatrix} \tag{17}$$

$$\begin{bmatrix} y_i(t) \\ y_q(t) \end{bmatrix} = \alpha_0 c(t) \begin{bmatrix} \cos(\phi_e) \\ sin(\phi_e) \end{bmatrix} \tag{18}$$

The signals after phase rotation are related to the gating signal, BOC signal and CA code, which can be respectively expressed as:

$$I_{yw}(\tau) = \frac{1}{T}\int_0^T y_i(t)w(t-\tau)dt = \frac{1}{T}\alpha_0 R_{xw}(\tau)cos(\phi_e) \tag{19}$$

$$I_{yx}(\tau) = \frac{1}{T}\int_0^T y_i(t)x(t-\tau)dt = \frac{1}{T}\alpha_0 R_{xx}(\tau)cos(\phi_e) \tag{20}$$

$$I_{yw}(\tau) = \frac{1}{T}\int_0^T y_i(t)w(t-\tau)dt = \frac{1}{T}\alpha_0 R_{cw}(\tau)cos(\phi_e) \tag{21}$$

$$I_{yc}(\tau) = \frac{1}{T}\int_0^T y_i(t)c(t-\tau)dt = \frac{1}{T}\alpha_0 R_{cc}(\tau)cos(\phi_e) \tag{22}$$

If Sine-BOC(1,1) and CA code use narrow correlator method to mitigate multipath effect, their phase discrimination functions can be expressed as:

$$\begin{aligned}
&I_{yx}(t+\frac{d}{2}-\tau)-I_{yx}(t-\frac{d}{2}-\tau) \\
&=\frac{1}{T}\int_0^T y_i(t)x(t+\frac{d}{2}-\tau)dt-\frac{1}{T}\int_0^T y_i(t)x(t-\frac{d}{2}-\tau)dt \\
&=\frac{1}{T}\int_0^T y_i(t)[x(t+\frac{d}{2}-\tau)-x(t-\frac{d}{2}-\tau)]dt \\
&=2I_{yw}(\tau)
\end{aligned} \tag{23}$$

$$\begin{aligned}
&I_{yc}(t+\frac{d}{2}-\tau)-I_{yc}(t-\frac{d}{2}-\tau) \\
&=\frac{1}{T}\int_0^T y_i(t)c(t+\frac{d}{2}-\tau)dt-\frac{1}{T}\int_0^T y_i(t)c(t-\frac{d}{2}-\tau)dt \\
&=\frac{1}{T}\int_0^T y_i(t)[c(t+\frac{d}{2}-\tau)-c(t-\frac{d}{2}-\tau)]dt \\
&=2I_{yw}(\tau)
\end{aligned} \tag{24}$$

3 Simulation and Performance Analysis

In this section, for the Sine-BOC(1,1) modulation signal, through MATLAB simulation experiments, the multi-path mitigation performance of narrow correlator technique and the gating signal correlation technique on BOC signal is simulated and analyzed, respectively. The simulation conditions are as follows: static environment with only one multipath signal, the amplitude ratio of the multipath signal to the direct signal is -6 dB and the influence of the receiver RF front-end bandwidth is negligible.

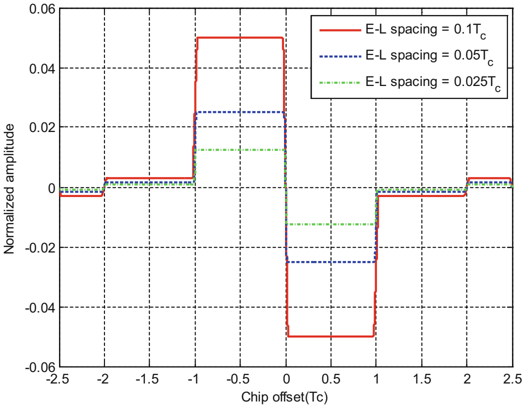

Fig. 3. Narrow correlator discriminator curve of BPSK

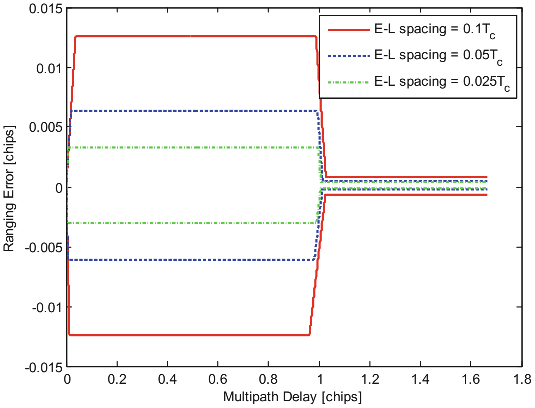

Fig. 4. Multipath error envelope for the BPSK signal with the narrow correlator

Based on the above theoretical derivation and analysis in Sect. 2, the BPSK signal and BOC signal using narrow correlator technique are simulated and analyzed in terms of multipath error. The simulation results are shown in Fig. 3 to Fig. 6.

As can be seen from Fig. 4, the narrow correlator technique has significant effect on BPSK signal multipath mitigation. With the smaller correlator interval, the better the multipath mitigation effect is. What's more, as shown in Fig. 3, the narrow correlation phase discrimination function does not have the phase discrimination ambiguity problem, because there is only one zero crossing point in the range of [−1Tc 1Tc], and there are no other false lock points. However, it is different for the BOC signal. Since the main peak of the autocorrelation function of the BOC signal is sharper than the CA code, its multipath mitigation effect is better relatively.

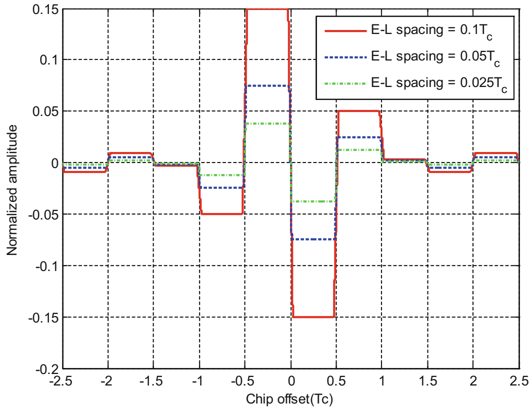

Fig. 5. Narrow correlator discriminator curve of BPSK Sine-BOC(1,1)

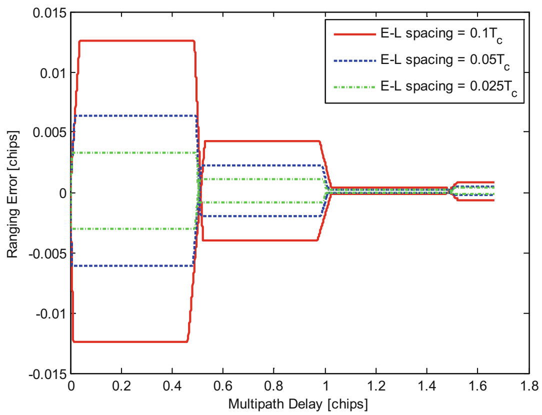

Fig. 6. Multipath error envelope for the Sine-BOC(1,1) signal with the narrow correlator

Figure 6 that Sine-BOC(1,1) has better multipath mitigation effect in the same correlator interval. However, the narrow correlation phase discrimination function of Sine-BOC (1,1) has ambiguity, because there are three zero-crossing points in the range of [−1 1] chips (as shown in Fig. 5), and the coordinates of the three zero-crossing points are −0.5, 0.5 and 0, respectively. This is because there are multiple side peaks in the autocorrelation function of the BOC signal. If the side peaks are eliminated thoroughly and the signal is correctly captured and tracked, BOC has a better multipath mitigation effect than BPSK.

The receiver signal processing block is shown in Fig. 7, the multi-path mitigation effect of the gating signal correlator and the narrow correlator method is shown in Fig. 8–13.

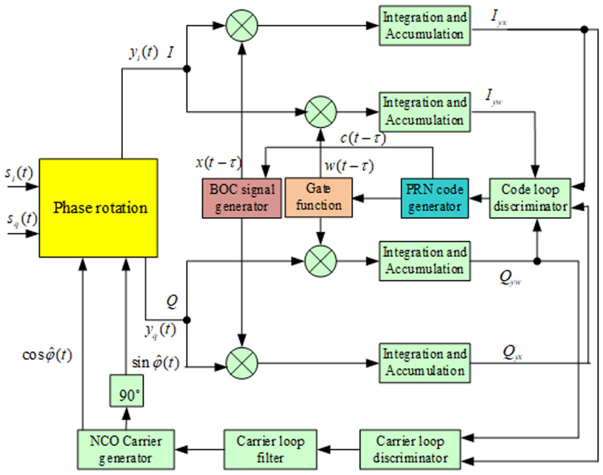

Fig. 7. Gating signal and block program of carrier loop signal processing

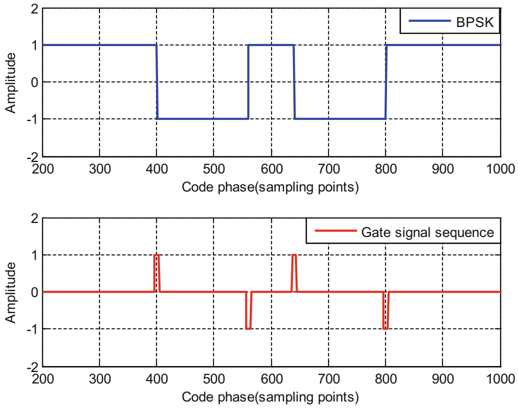

Fig. 8. Gating signal corresponding to BPSK

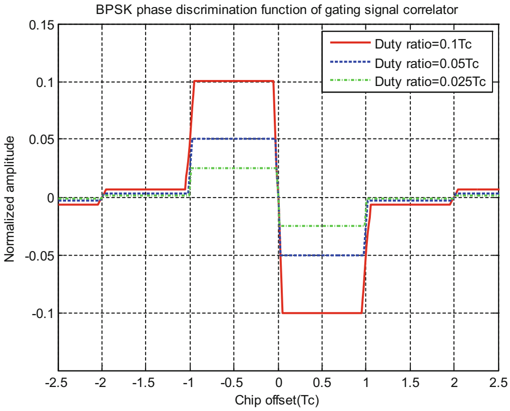

Fig. 9. BPSK phase discrimination function of gating signal correlator

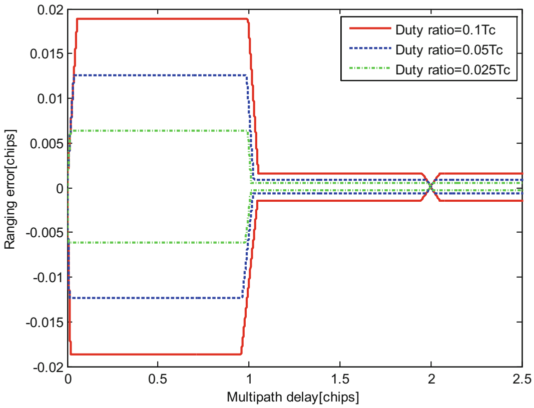

Fig. 10. Multipath error envelope for the BPSK signal with gating signal

Figure 8 is a gating signal corresponding to BPSK. The gating signal has the same period as the CA code, and the influence of the CA code is considered, so the waveform of the gating signal corresponds to the phase inversion position of the CA code. The cross-correlation function of the gating signal and the input signal is directly used as the phase discrimination function of the code tracking loop, phase discrimination curve is shown in Fig. 9 and its multipath error envelope curve is shown in Fig. 10. It can be seen from the error envelope curve that the smaller the duty ratio of the gating signal, the smaller the multipath error.

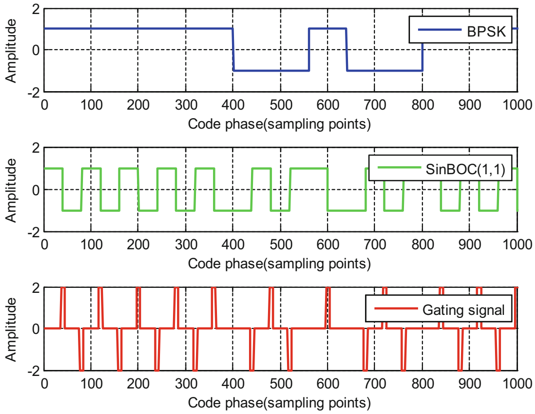

Fig. 11. Gating signal corresponding to Sine-BOC(1,1)

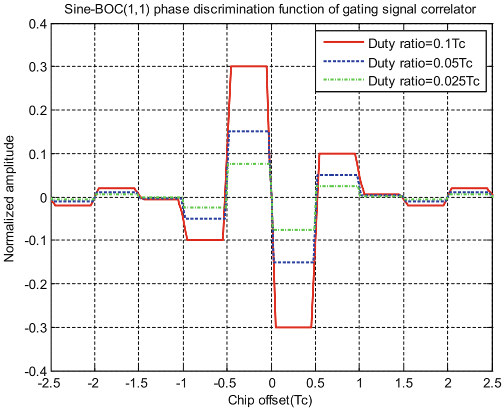

Fig. 12. Sine-BOC(1,1) phase discrimination function of gating signal correlator

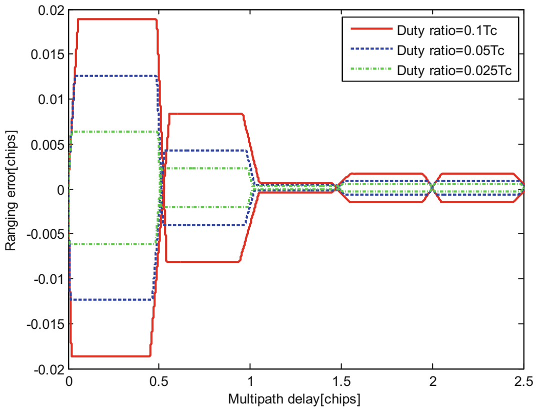

Fig. 13. Multipath error envelope for the Sine-BOC(1,1) signal with gating signal

Figure 11 is the gating signal corresponding to Sine-BOC(1,1). Compared with the BPSK gating signal, it considers the influence of subcarrier. The phase discrimination function is shown in Fig. 12. Like the phase discrimination function of the narrow correlator, the gating signal also has the problem of phase discrimination ambiguity. The multipath error envelope curve is shown in Fig. 13. Compared with the BPSK multipath error envelope curve, the Sine-BOC(1,1) multipath error is smaller,, and the multipath error is half of BPSK in the range of 0.5 to 1 chip, especially.

4 Conclusion

As a new type of navigation signal, BOC has many advantages, such as the sharper main peak and high ranging accuracy. However, multipath error is still one of its main sources of error. In this paper, the multipath mitigation effect of BPSK and BOC signals using narrow correlator method is analyzed and compared. The study shows that the BOC narrow correlator phase discrimination function has phase discrimination ambiguity. The BOC signal must be accurately captured and tracked in order to have a good multipath mitigation effect. According to the theoretical formula derivation and simulation, the gating signal correlator and the narrow correlator method have the same effect on multipath mitigation. When the correlation function of the gating signal can be used as the phase discrimination function of the code tracking loop of the BPSK signal, there is no problem of phase discrimination ambiguity. However, the correlation function of the gating signal as the phase discrimination function of the code tracking loop of the BOC signal has the problem of ambiguity. Therefore, when the traditional narrow correlator and gating signal correlator methods are used for multipath mitigation of BOC signals, measures must be taken to ensure that the signals are used under the premise of correct acquisition and tracking.

References

1. Braasch, M.S., Van Graas, F.: Guidance accuracy considerations for real-time GPS interferometry. In: Institute of Navigation GPS 91 conference, Albuquerque, New Mexico, pp. 373–386, 11–13 Sept. 1991
2. Patrick, C., Fenton, J.J.: The Theory and performance of NovAtel Inc.'s vision correlator. In: ION GNSS 2005 Long Beach, CA (2005)
3. Fenton, P., Falkenberg, B., Ford, T., Ng, K., Van Dierendonck, A.J.: NovAtel's GPS receiver-the high performance oem sensor of the future. In: Proceedings of ION GPS-91, Fourth International Technical Meeting of the Division Satellite of the Institute of Navigation, Albuquerque, NM, pp. 49–58, 11–13 Sept. 1991
4. Van Dierendonck, A.J., et.al.: Theory and performance of narrow correlator spacing in a GPS receiver. J. Instit. Navig. **39**(3), 265–283 (1992)
5. Trautenberg, H.L., Weber, T., Schafer, C.: GALILEO system overview. Acta Astronaut. **55**, 643–647 (2004)
6. Wallner, S., Hein, G., Pany, T., Rodriguez, J.A., Posfay, A.: Interference computation between GPS and Galileo. In: Proceedings of ION GNSS, pp. 861–876, Long Beach, CA (2005)
7. Betz, J.W.: Binary offset carrier modulations for radio navigations. J. Inst. Navig. **48**, 227–246 (2002)
8. Ji, Y.F., Shi, H.L., Sun, X.Y.: A strobe correlator and its multipath suppression performance research. J. Astro. **28**(5), 1094–1099 (2007)
9. Van Dierendonck, A.J., Fenton, P.C., Ford, T.J.: Theory and performance of narrow correlator spacing in a GPS receiver. Navigation **39**(3), 265–283 (1992)
10. Wu, J., Dempster, A.G.: The "BOC-Gated-PRN", A novel unambiguous multipath mitigation technique for BOC (n, n) Modulation Waveform. submitting to IEEE Transactions on Aerospace and Electronic Systems (2008)