Unambiguous Tracking Method Based on Combined Correlation Functions for sine/cosine-BOC CBOC and AltBOC Modulated Signals

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Abstract. *Unambiguous tracking for Binary Offset Carrier (BOC) modulated signals is an important requirement of modern Global Navigation Satellite System (GNSS) receivers. An unambiguous tracking method based on combined correlation functions for even/odd order sine/cosine-BOC, Composite BOC (CBOC) and Alternate BOC (AltBOC) modulated signals is proposed. Firstly, a unified mathematical formulation for all kinds of BOC modulations is introduced. Then an unambiguous tracking method is proposed based on the formulation and the idea of pseudo correlation function (PCF) method. Finally, the tracking loop based on the proposed method is designed. Simulation results indicate that the proposed method can remove side peaks while retaining the sharp main peak for all kinds of BOC modulations. The tracking performance for AltBOC is examined and the results show that the proposed method has better performance in thermal noise and long-delay multipath mitigation than the traditional unambiguous tracking methods.*

Keywords

Global Navigation Satellite Systems (GNSS), Binary Offset Carrier (BOC), unambiguous tracking, multipath.

1. Introduction

In recent years, advances in modernized Global Navigation Satellite Systems (GNSS) have generated higher requirements for system performance [1]. For example, the higher accuracy positioning and location services are needed for modernized GPS, the European Galileo and the Chinese Compass systems while these systems should also preserve compatibility and keep interference levels at minimum. Based on the experience gained during the traditional GPS operation, a new modulation, namely, the Binary Offset Carrier (BOC) modulation was designed to meet these challenges [2]. This modulation moves the signal energy away from the center of the spectrum, thus enabling effective frequency sharing [3]. Several kinds of BOC modulations including sine-BOC (sBOC), cosine-BOC (cBOC), Composite Binary Offset Carrier (CBOC), and Alternate BOC (AltBOC) were proposed to cope with various situations. These BOC modulations can achieve better accuracy and lower multipath error than Binary Phase Shift Keying (BPSK) modulation which was commonly used in traditional GPS system [2]. However, BOC modulations also bring some new problems; the most severe one is tracking ambiguity [4]. Due to the multiple side peaks in the auto-correlation function (ACF) of BOC modulated signals, the receiver may false lock onto one of the side peaks in tracking process. This false lock would then result in a large and irreparable tracking error.

Several solutions were proposed to alleviate this problem, including the BPSK-Like [5], bump-jumping (BJ) [6], and side-peaks cancellation (SC) techniques [7]. The BPSK-Like technique implements a pair of single sideband correlations to remove the effect of the sub-carrier. This method treats each lobe of BOC signal independently as a BPSK signal that has a correlation function with single peak, thus allowing the use of the traditional tracking method. However, the sharp main peak of the BOC signal's ACF is destroyed in this method, losing the robustness against thermal noise and multipath [4]. The BJ technique employs two additional correlators located at the theoretical location of the side peaks to determine whether false lock occurs. When the tracking loop is locking onto the main peak, the tracking performance of this technique is corresponded to the performance of standard tracking loops, but after the occurrence of the false lock, BJ technique has a long resetting time due to its logic decision process [7].

SC techniques are innovative methods to solve ambiguity. SC techniques involve using new local replica signals whose chip waveforms are different from that of the received signal and combining the correlation outputs to generate an unambiguous correlation function [8]. The most representative methods of this kind are the autocorrelation side-peak cancellation technique (ASPeCT) [9] and the Sub Carrier Phase Cancellation (SCPC) [6]. ASPeCT is simple and effective, but it can only apply to BOC(n,n)

signals. SCPC employs in-phase and quadrature-phase local signals to obtain a combined unambiguous correlation function. The shape of this function is similar to the one of the BPSK-Like so they have the same disadvantage. The pseudo correlation function (PCF) is another representative SC technique [10]. PCF employs two local replica signals to generate an unambiguous pseudo correlation function whose peak is as narrow as the main peak of the ACF, thereby, ensuring that this method has preserved the BOC's capability of tracking accuracy. The PCF is based on a mathematical formulation proposed in [8] which is used to express the BOC modulated signals. However, the mathematical formulation in the PCF method is only suitable to the sBOC of even order. Therefore, only the unambiguous tracking method for even order sBOC is given.

To solve the ambiguity problem for all kinds of BOC modulated signals, including the odd and even order, sine and cosine phase, and the composite or complex modulations such as CBOC and AltBOC, a unified and simple mathematical formulation is needed for all these BOC modulations. In [11], we have proposed a unified signal model which contains a unified mathematical formulation and cross-correlation function (CCF) formula for all these BOC modulated signals. Based on these formulas and the concept of PCF, in this paper, we propose an unambiguous tracking method. This method can maintain the narrow peak and is suitable for all kinds of BOC modulated signals. Finally, an unambiguous tracking loop based on the proposed method is given.

The remainder of this paper is organized as follows: in Section 2, the unified mathematical formulation and the CCF formula of the BOC modulations are introduced. Section 3 proposes an unambiguous tracking method based on the proposed formulas. Section 4 designs tracking loop for the proposed method. Section 5 investigates the tracking performance of the proposed method, and conclusions are presented in Section 6.

2. Unified Mathematical Formulation of Different Kinds of BOC Modulated Signals

BOC modulation is a square sub-carrier modulation in which the Direct Sequence Spread Spectrum (DSSS) signals are multiplied by a rectangular sub-carrier [2]. A BOC modulation is denoted as BOC(α,β), which means that the subcarrier frequency is $f_B = \alpha \times 1.023$ MHz and the spreading code rate is $f_c = \beta \times 1.023$ MHz, α and β are the positive real numbers. The BOC modulation order N_{BOC} is given by

$$N_{BOC} = \frac{2f_B}{f_C} = \frac{T_C}{T_B} = 2\frac{\alpha}{\beta} \tag{1}$$

where $T_c = 1/f_c$ refers to the spreading code chip period and $T_B = 1/2f_B$ is the period of one subcarrier chip and α, β should be carefully selected to make N_{BOC} to be a positive integer.

The sBOC or cBOC modulated signal $s(t)$ can be expressed as the convolution between a sine/cosine BOC waveform $s_{s/c\,BOC}(t)$ and a spreading code sequence C_k, as follows

$$s(t) = \sum_{k=-\infty}^{+\infty} C_k \otimes s_{s/c\,BOC}(t) \tag{2}$$

where $\{C_k\}$ represents the spreading sequence of binary digits $\{-1,1\}$, $\otimes$ represents the convolution operator, and $s_{s/c\,BOC}(t)$ can be expressed as

$$\begin{cases} s_{s\,BOC}(t) = sign(\sin(\dfrac{N_{BOC}\pi t}{T_c})), & 0 \le t < T_c \\ s_{c\,BOC}(t) = sign(\cos(\dfrac{N_{BOC}\pi t}{T_c})), & 0 \le t < T_c \end{cases} \tag{3}$$

where sign(.) is the signum operator. The sine/cosine BOC signals can be denoted as sBOC(α,β) and cBOC(α,β), respectively, and the CBOC, AltBOC are denoted as CBOC(α,β,κ) and AltBOC(α,β), where the α and β are the same meaning as above-mentioned and κ is the percentage of power of BOC(α,1) with respect to the total CBOC signal power.

We use the Dirac function $\delta(t)$ property: $s(t) = \int_{-\infty}^{+\infty} s(\tau)\delta(t-\tau)\mathrm{d}\tau$ and the step-shape modulated symbols concept [8] to build a unified formulation. Equation (2) can then be equally expressed as

$$s(t) = \sum_{k=-\infty}^{+\infty} C_k \otimes p_{T_S}(t) \otimes \sum_{m=0}^{N-1} d_m \delta(t - mT_S) \tag{4}$$

where $p_{T_S}(t)$ is the rectangular pulse of amplitude 1 defined via

$$p_{T_S}(t) = \begin{cases} 1 & 0 \le t < T_S \\ 0 & otherwise \end{cases} \tag{5}$$

T_S denotes the step-shape symbol time, which means the duration of each symbol. $N = T_C / T_S$ is the number of step-shape symbols. $\boldsymbol{d} = [d_0, d_1, \cdots d_{N-1}]_{N\times1}$ is the step-shape symbol bits vector, which can represent the waveform of the subcarrier in one cycle. Details on the determination of T_S and $\boldsymbol{d}$ can be found in [11]. For simplicity, we only give the main cases here.

Case 1: For even order sBOC, $T_S = T_B$, $\boldsymbol{d} = [1,-1,\ldots,-1]_{N_{BOC}\times1}$. For example, in the case of sBOC(1,1), $T_S = T_C/2$ and $\boldsymbol{d} = [1,-1]_{2\times1}$. The step-shape symbols are shown in Fig. 1.

Case 2: For even order cBOC, $T_S = T_C/(2N_{\mathrm{BOC}}) = T_B/2$, $\boldsymbol{d} = [1,-1,-1,1,\ldots,1]_{2N_{BOC}\times1}$. For example, in the case of cBOC(1,1), $T_S = T_C/4$ and $\boldsymbol{d} = [1,-1,-1,1]_{4\times1}$. The step-shape symbols are shown in Fig. 2.

Case 3: For odd order BOC, it can be thought of as the baseband spreading code sequence C_k of the modulated signal is replaced by the code $(-1)^k C_k$. Then T_S and $\boldsymbol{d}$ can be obtained according to case 1 or case 2.

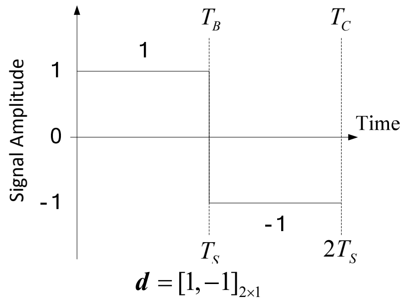


Fig. 1. Step-shape symbols of even order sBOC(1,1).

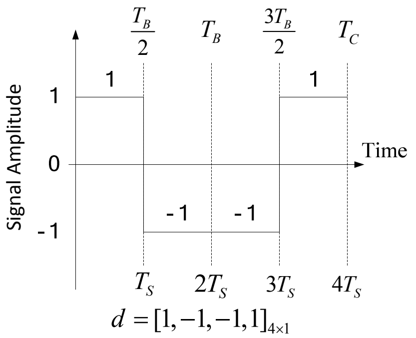


Fig. 2. Step-shape symbols of even order cBOC(1,1).

Case 4: For CBOC, a composite step-shape symbol is used. Taking CBOC(6,1,1/11) for example, $T_S = T_C/12$ and

$$\boldsymbol{d} = \sqrt{10/11} \times \boldsymbol{d}_{BOC(1,1)} + \sqrt{1/11} \times \boldsymbol{d}_{BOC(6,1)} \tag{6}$$

where

$\boldsymbol{d}_{BOC(1,1)} = [\underbrace{1,1,\ldots,1}_{6},\underbrace{-1,\ldots,-1}_{6}]_{12\times1}$, $\boldsymbol{d}_{BOC(6,1)} = [1,\text{-}1,\ldots,1,\text{-}1]_{12\times1}$.

Case 5: For AltBOC, an imaginary part is added to (4), and (4) is rewritten as

$$\begin{cases} s(t) = s^{(r)}(t) + js^{(i)}(t) \\ s^{(r)}(t) = x^{(r)}(t) \otimes p_{T_{S^{(r)}}}(t) \otimes \sum\limits_{m=0}^{N^{(r)}-1} d_m^{(r)} \delta(t - mT_{S^{(r)}}) \\ s^{(i)}(t) = x^{(i)}(t) \otimes p_{T_{S^{(i)}}}(t) \otimes \sum\limits_{m=0}^{N^{(i)}-1} d_m^{(i)} \delta(t - mT_{S^{(i)}}) \end{cases} \tag{7}$$

where the superscript r, i represent two independent modulated signals for the real and imaginary part of the complex signals, respectively. Taking AltBOC(15,10) for example, this modulation can be seen as a combination of sBOC(15,10) modulation for the real part and cBOC(15,10) modulation for the imaginary part [12].

$$\begin{cases} d^{(r)} = [1,-1,1] \\ d^{(i)} = [1,-1,-1,1,1,-1] \end{cases} \tag{8}$$

The CCF between the received signal and a different local signal is also used in the tracking process of the PCF methods [10]. The CCF between two signals expressed by (7) is given as

$$R(\tau) = R^{(rr)}(\tau) + R^{(ii)}(\tau) + 2jR^{(ri)}(\tau) \tag{9}$$

where $R^{(rr)}(\tau)$, $R^{(ii)}(\tau)$, and $R^{(ri)}(\tau)$ can be understood as the CCF between the two real parts, the CCF between the two imaginary parts, and the CCF between the real part and the imaginary part of the two signals, respectively. After unifying the number of the step-shape symbols to N and resampling step-shape symbol bits vectors following the steps in [11], the normalized $R^{(rr)}(\tau)$can be obtained as:

$$R^{(rr)}(\tau) = \frac{1}{N} \sum_{m=0}^{N-1} \sum_{m_1=0}^{N-1} d_m^{(r)} d_m'^{(r)} \Lambda_{T_S}(\tau - (m - m_1)T_S) \tag{10}$$

where the $\Lambda_{T_S}(\tau)$ is a triangle function with the baseline width of T_S. The $R^{(ii)}(\tau)$ and the $R^{(ri)}(\tau)$ have the same form as (10).

3. Proposed Unambiguous Tracking Method

The PCF method is an innovative unambiguous tracking method that uses local replica signals which are designed carefully to correlate with the received signal, and then the correlators' outputs are combined to obtain a correlation function with the sharp main peak only [8]. The PCF method performs well in tracking BOC signals. However, the PCF method is only suitable to even order sBOC due to the limitation of its mathematical formulation [8]. Based on the idea of the PCF method and the proposed mathematical formulation, a newly developed unambiguous tracking method that is suitable to all kinds of BOC modulations is given in this section.

In the first step, we only considered the real signal. From the CCF formula (9), the shape of CCF is obtained from the combined triangular shapes $\Lambda_{T_S}(\tau - kT_S)$, which have peaks at the delay kT_S. The values of these peaks are defined as

$$\begin{aligned} r_k &= \frac{1}{N} \sum_{i=0}^{N-1-k} d_i d'_{i+k} \quad 0 \le k \le N-1 \\ &= \frac{1}{N} \sum_{i=0}^{N-1+k} d_{i-k} d'_i \quad 1-N \le k < 0 \end{aligned} \tag{11}$$

The value of combined triangular shapes at kT_S is r_k and is piecewise linear between kT_S and $(k+1)T_S$ because the width of the triangular $\Lambda_{T_S}(\tau - kT_S)$ is $2T_S$, and the peak is located at the zero points of the adjacent triangle.

This means that the shape of CCF is determined by $R(kT_S) = r_k$, for $k \in [1-N, N-1]$ and $k \in \mathbb{Z}$. The r_k is designated as the shape point of the correlation function.

Assuming that $s(t)$ is the local replica signal and $s'(t)$ is the received signal, the step-shape symbol of the received signal $\boldsymbol{d}'$ is constant in a receiver. Thus, the shape of CCF is determined by the local replica signals' symbol $\boldsymbol{d}$ which should be designed. As in the PCF method, two local signals, whose symbol vectors are $\boldsymbol{d}^{(1)}$ and $\boldsymbol{d}^{(2)}$, are employed here and the combined correlation function is defined as:

$$R_P(\tau) = |R_1(\tau)| + |R_2(\tau)| - |R_1(\tau) + R_2(\tau)| \tag{12}$$

where $R_1(\tau)$ and $R_2(\tau)$ are CCFs between the received signal and the two local signals. The combined function (12) is called antisymmetry side peaks cancellation criterion, which is chosen to use in the PCF method, because when $R_1(\tau)$ and $R_2(\tau)$ are symmetrical and the shapes are carefully designed, the combined function can generate a correlation function without side peaks.

To obtain a symmetrical correlation shape, the condition $R_2(\tau) = -R_1(-\tau)$ should be satisfied [11]. Considering the shape point (11) this condition is equivalent to:

(1) for odd order sBOC and even order cBOC: $d_i^{(2)} = -d_{N-i-1}^{(1)}$, $i = 0,1,2,\cdots N-1$;

(2) for even order sBOC, odd order cBOC and CBOC: $d_i^{(2)} = d_{N-i-1}^{(1)}$, $i = 0,1,2,\cdots N-1$.

We only need to design the shape symbol $\boldsymbol{d}^{(1)}$ because of this condition and the $\boldsymbol{d}^{(2)}$ can be obtained according to $\boldsymbol{d}^{(1)}$.

To ensure that the correlation shape is triangular without side-peaks, the proposed correlation function must satisfy the following condition:

$$\begin{cases} R_P(0) \neq 0 \\ R_P(\tau) = 0, \tau \in [T_s, NT_s] \cup [-T_s, -NT_s] \end{cases} \tag{13}$$

Due to the piecewise linear characteristic of CCF, it can be proved that the necessary condition to satisfy the request (13) are

$$\begin{cases} r_k^{(1)} r_{-k}^{(1)} \leq 0, k \neq 0 \\ r_0^{(1)} \neq 0 \end{cases} \tag{14}$$

Condition (14) can remove the peaks at kT_S, $k \neq 0$. However, the modulus operation in (12) may add new shape points at the zero crossing points of the correlation function. Assuming that $R_1(\tau)$ has a zero crossing point τ_0 in the range $[kT_S, (k+1)T_S]$, then

$$\tau_0 = kT_S + \frac{|r_k|}{|r_k| + |r_{k+1}|} T_S . \tag{15}$$

For $R_2(\tau)$, a zero crossing point must be located at the same place. Therefore, when $r_k r_{k+1} < 0, (k > 0)$, the condition

$$r_k r_{-k-1} = r_{-k} r_{k+1} \tag{16}$$

should be satisfied.

Substituting (11) into (14) and (16), the cases are equivalent to:

Case 1: For odd order sBOC and even order cBOC:

$$\begin{cases} d_0^{(1)} > 0, d_{N-1}^{(1)} < 0 \\ d_i^{(1)} = 0, 0 < i < N-1 \end{cases} \tag{17}$$

Case 2: For even order sBOC, odd order cBOC and CBOC:

$$\begin{cases} d_0^{(1)} > 0, d_{N-1}^{(1)} > 0 \\ d_i^{(1)} = 0, 0 < i < N-1 \end{cases} \tag{18}$$

Then, by considering the energy normalized condition:

$$\sum_{i=0}^{N-1} (d_i^{(1)})^2 = N . \tag{19}$$

The step-shape symbols of two local replica signals are:

Case 1: For odd order sBOC and even order cBOC:

$$\begin{cases} \boldsymbol{d}^{(1)} = [\sqrt{\frac{N}{1+x^2}}, 0, \cdots, 0, -x\sqrt{\frac{N}{1+x^2}}]_{N\times1} \\ \boldsymbol{d}^{(2)} = [x\sqrt{\frac{N}{1+x^2}}, 0, \cdots, 0, -\sqrt{\frac{N}{1+x^2}}]_{N\times1} \end{cases} \tag{20}$$

Case 2: For even order sBOC, odd order cBOC and CBOC:

$$\begin{cases} \boldsymbol{d}^{(1)} = [\sqrt{\frac{N}{1+x^2}}, 0, \cdots, 0, x\sqrt{\frac{N}{1+x^2}}]_{N\times1} \\ \boldsymbol{d}^{(2)} = [x\sqrt{\frac{N}{1+x^2}}, 0, \cdots, 0, \sqrt{\frac{N}{1+x^2}}]_{N\times1} \end{cases} \tag{21}$$

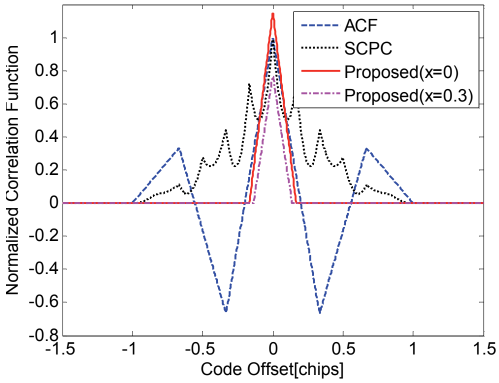
where $x \in [0,1)$ is a tunable parameter. The result for even order sBOC is the same as [8], but the results for other kinds of BOC modulations are not discussed there.

Case 3: The AltBOC modulation is a combination of two signals. Thus, we used two complex local signals to deal with the sBOC and cBOC. The symbol vectors of these two local signals are $\boldsymbol{d}^{(1)(r)}$, $\boldsymbol{d}^{(1)(i)}$ and $\boldsymbol{d}^{(2)(r)}$, $\boldsymbol{d}^{(2)(i)}$ as

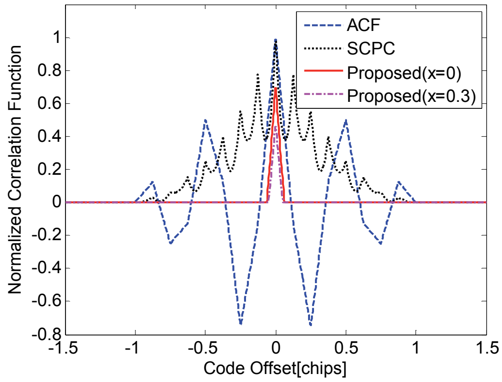
$$\begin{cases} \boldsymbol{d}^{(1)(r)} = [\sqrt{\frac{N}{1+x^2}}, 0, \cdots, 0, -x\sqrt{\frac{N}{1+x^2}}]_{N\times1} \\ \boldsymbol{d}^{(1)(i)} = [\sqrt{\frac{N}{1+x^2}}, 0, \cdots, 0, x\sqrt{\frac{N}{1+x^2}}]_{N\times1} \\ \boldsymbol{d}^{(2)(r)} = [x\sqrt{\frac{N}{1+x^2}}, 0, \cdots, 0, -\sqrt{\frac{N}{1+x^2}}]_{N\times1} \\ \boldsymbol{d}^{(2)(i)} = [x\sqrt{\frac{N}{1+x^2}}, 0, \cdots, 0, \sqrt{\frac{N}{1+x^2}}]_{N\times1} \end{cases} \tag{22}$$

The shapes of the proposed correlation functions with $x = 0$ and $x = 0.3$ for six representative BOC modulations including sBOC(15,10) which is odd order, cBOC(10,5) which is even order, sBOC(10,5) which is even order, cBOC(15,10) which is odd order, CBOC(6,1,1/11) and AltBOC(15,10) are shown in Fig. 3. For comparison, the ACFs and the shapes generated by SCPC method which is also suitable for all kinds of BOC modulations are also given in Fig. 3.

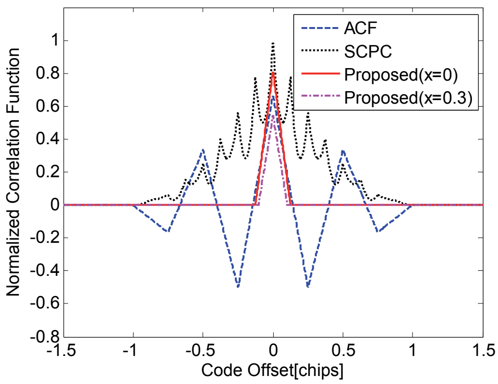
Fig. 3. shows that the correlation functions generated from the SCPC method is similar with that of BPSK, and this method destroys the narrow peak of ACF. In contrast to the SCPC method, the proposed method removes all the side peaks while maintaining the sharp shape of the main peak. Fig. 3. also shows that with the increase of x, the



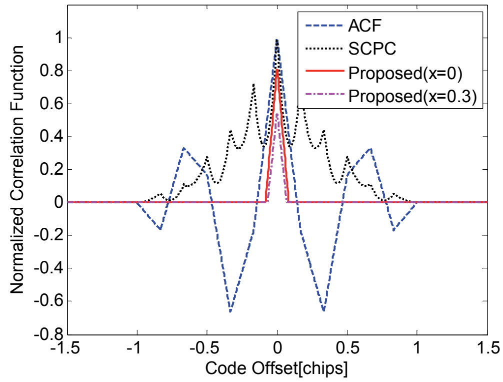
a. sBOC(15,10)



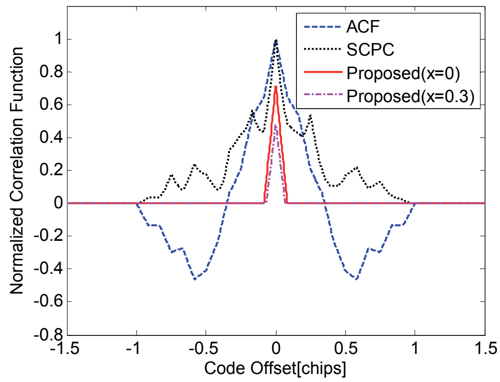
b. cBOC(10,5)



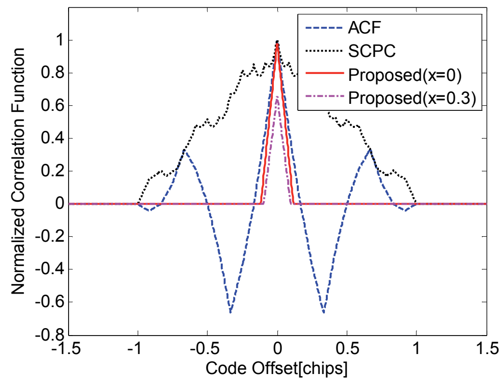
c. sBOC(10,5)



d. cBOC(15,10)



e. CBOC(6,1,1/11)



f. AltBOC(15,10)

Fig. 3. Normalized correlation functions comparison with ACF, SCPC and the proposed method.

peak height decreases and the baseline width narrows. When x comes close to 1, the peak may be too low for being tracked. This finding may change the multipath and thermal noise mitigation performances of the tracking loop.

The above result leads us to conclude that the PCF method is a special case of the proposed method for even order sBOC, and that the proposed method has a more generic applicability than the PCF method. Six kinds of BOC modulations are shown in Fig. 3, however, for the sake of simplicity and without loss of generality, AltBOC(15,10), which is the combination of two kinds of BOC modulation and is the most complicated modulation, is discussed hereafter in this paper.

4. Implementation of the Proposed Method

A new architecture of the non-coherent narrow Early-Minus-Late (NEML) tracking loop for AltBOC(15,10) is presented in Fig. 4 based on the proposed unambiguous correlation function. The received AltBOC(15,10) signal is first multiplied with the local carrier, and then down converted to baseband in-phase (*I*) and quadrature-phase (*Q*) signals. The local signal generator generates early and late local signals with spacing Δ according to the step-shape symbols $\boldsymbol{d}^{(1)(r)}$, $\boldsymbol{d}^{(1)(i)}$, $\boldsymbol{d}^{(2)(r)}$, and $\boldsymbol{d}^{(2)(i)}$, which are defined as (22). The local signals are multiplied by the baseband *I* and *Q* signals, and the results are integrated with the duration time T_{int}. The proposed correlation function can be expressed as:

$$R_p(\tau,x)=\sqrt{I_1^2+Q_1^2}+\sqrt{I_2^2+Q_2^2}-\sqrt{(I_1+I_2)^2+(Q_1+Q_2)^2} \quad (23)$$

The discriminator output based on this correlation function is given as:

$$D_p(\tau,x)=(R_P^{(E)}(\tau,x))^2-(R_P^{(L)}(\tau,x))^2 \quad (24)$$

where the superscripts *E* and *L* indicate the early and late branch.

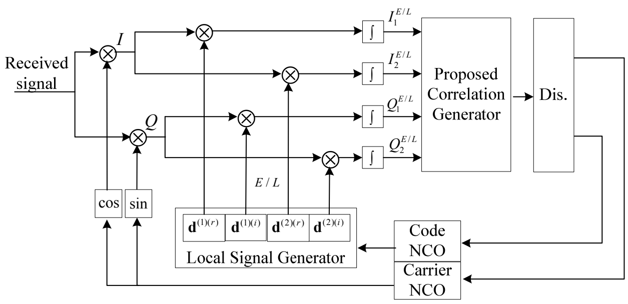


Fig. 4. New unambiguous DLL architecture for AltBOC(15,10).

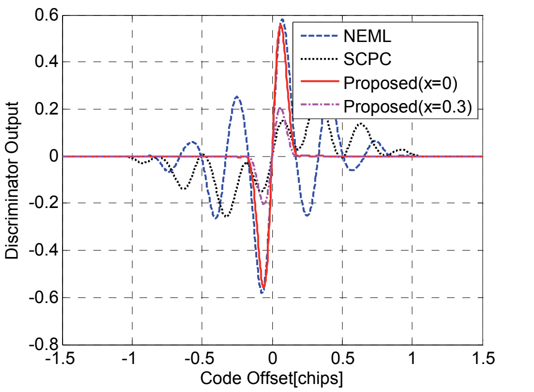


Fig. 5. Discriminator outputs comparison for traditional NEML loop, SCPC method and the proposed method, with 90 MHz front-end filter.

Fig. 5 shows the discriminator outputs $D_p(\tau,0)$ and $D_p(\tau,0.3)$ with a 90 MHz bandwidth frontend filter and the early-late spacing $\Delta = 0.1$ chips. The discriminator curves from the traditional NEML loop and SCPC method is also shown.

It can be seen that the NEML loop has some false lock points, which would result in intolerable biased measurements, while both the SCPC method and the proposed method can remove the false lock points. Compared with the SCPC method, the proposed method has higher sensitivity, which is defined as [13]:

$$\left.\frac{dD(\tau)}{d\tau}\right|_{\tau=0} \quad (25)$$

This means that the proposed method has a smaller residual error.

5. Performance Evaluations

The thermal noise range error is an important criterion of the tracking performance. It is determined by the shape of main peak of correlation function. Fig. 6 shows the code tracking noise standard deviation of the proposed method for AltBOC(15,10) with the integrate time $T_{\text{int}} = 1$ ms, the early-late spacing $\Delta = 0.1$ chips and the single-sided loop filter bandwidth $B_L = 2$ Hz by Monte Carlo simulations. According to [8], the parameter *x* is usually under 0.3, so we use $x = 0$ and $x = 0.3$ to exam the performance. For comparison, the standard deviation of the BPSK-Like, and the SCPC method, which can be applied to AltBOC modulation, is also given.

We can discover that the BPSK-Like method has the worst performance among the other methods and the proposed method performs slight better than the SCPC method because the main peak of the proposed correlation function is sharper than the one of SCPC. Based on Fig. 6, we may conclude that the selection of the parameter *x* has an effect on the noise performance. For low and medium C/N_0, a larger x indicates the better accuracy.

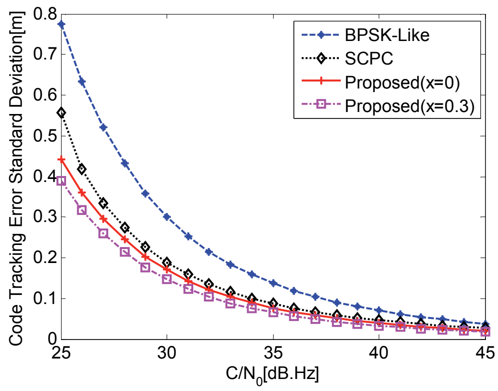


Fig. 6. Code tracking error standard deviation versus C/N_0, with 90 MHz front-end filter.

The multipath error is generated because the line-of-sight signal is corrupted by the delayed reflected signal. It is another dominant error source of signal tracking. Typically, the criterion to evaluate the multipath mitigation performance of a tracking method is the multipath error envelope (MEE), which commonly uses two paths, both in-phase and out-of-phase to calculate. The amplitude of the second-path is 6 dB lower than that of the line-in-sight path and the early-late spacing $\Delta = 0.1$ chips [14]. The MEEs obtained from the unambiguous tracking methods are illustrated in Fig. 7.

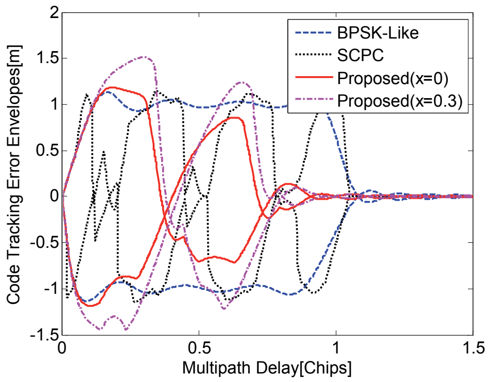


Fig. 7. Code tracking error envelopes of multipath error.

The results show that, when $x = 0.3$, for the multipath delay that ranges from 0 to 0.3 chips and 0.5 to 0.7 chips, the proposed method is inferior to the BPSK-Like. This finding seems incompatible with the fact that the proposed correlation function has a sharp main peak, as illustrated in Fig. 5. However, one should note that the proposed correlation function is obtained from the non-coherent combination of two CCFs which do not have narrow peaks. This nonlinear combination makes the proposed method more susceptible to multipath. The results of the comparison between the SCPC and the proposed method are different in terms of delay ranges. In the range from 0 to 0.6 chips, identifying which of the two methods is superior is difficult, whereas in the range after 0.6 chips, the proposed method performs better than the SCPC and BPSK-Like methods. The resultant figure indicates that with the decrease of x, the multipath mitigation performance of the proposed method improves. When $x = 0$, in the range after 0.3 chips, the proposed method can have better performance than the other two methods.

6. Conclusions

In this paper, a new unambiguous tracking method for BOC modulated signals is presented. This method extends the applicability of PCF method to all kinds of BOC modulations. The proposed method can completely remove the side peaks in the correlation functions. The tracking performance evaluations for AltBOC shows that the proposed method can achieve better performance with respect to thermal noise and multipath mitigation compared with the traditional unambiguous tracking methods. Besides, the unambiguous tracking loop is designed based on the proposed method and it is easily implemented in GNSS receives. Future works will focus on the detailed performance evaluations for the proposed method and the impact of the parameter x.

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