TELKOMNIKA, Vol.13, No.2, June 2015, pp. 502 ~ 509
ISSN: 1693-6930, accredited A by DIKTI, Decree No: 58/DIKTI/Kep/2013
DOI: 10.12928/TELKOMNIKA.v13i2.1469

Unambiguous Sine-Phased BOC (kn,n) Signal Acquisition Based on Combined Correlation Functions

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Abstract

Galileo and GPS have been developing their new signals in recent years. Multiplexed Binary Offset Carrier (MBOC) is the final implementation of Galileo E1 and GPS L1C, which is the multiplexing of BOC (1,1) and BOC (6,1). Therefore, it is helpful to satisfy the demand that the new signals must be compatible with GPS BPSK signal. BOC (kn,n) modulation will provide better track performance and higher positioning accuracy. However, the main drawback of the BOC modulated signal is that its autocorrelation has multiple side peaks around the main peak. This paper will focus on a family of signals: sine-phased BOC (kn,n). We are trying to explore a new method to cancel the side peaks of BOC (kn,n) autocorrelation, making use of two kinds of correlation functions. One is the correlation of the incoming signal and the sine-phased BOC (kn,n) modulated spreading code(PRN code multiplied by subcarrier), and the other is the correlation of the incoming signal and the PRN code only. Two kinds of correlation function are separated into several sub-correlations. Sub-correlations have less side peaks which are in different code delays. Corresponding parts of two sub-correlations will be combined to cancel the side peaks separately, and finally the new function without side peaks will be acquired after several correlations added together. Simulation results will be given. It is shown that the proposed method is contributed to the side peaks cancellation for unambiguous sine-phased BOC (kn, n) signal acquisition.

Keywords: *Sine-Phased BOC (kn,n) Signal, Unambiguous Acquisition, Combined Correlation Functions*

1. Introduction

Galileo and GPS have been developing their new signals in recent years. In the new generation of Global Navigation Satellite Systems (GNSSs), Multiplexed Binary Offset Carrier (MBOC) modulation is recommended for the GPS L1C signal and the Galileo E1 OS signal [1]. The MBOC modulation places a small amount of additional power at high frequencies in order to improve signal tracking performance, which is the multiplexing of BOC (1,1) and BOC (6,1). The Binary Offset Carrier (BOC) modulation can split spectrum into two main lobes shifted from the center frequency by the frequency of the subcarrier. The common notation for BOC-modulated signals in the GNSS field is BOC (f_s , f_c) where f_s is the frequency of the sub-carrier, and f_c represents the spreading code chip rate. Both f_s and f_c are usually noted as a multiple of the reference frequency of 1.023 MHz. Therefore, BOC-modulated signals are also noted as BOC (m,n), where m means the ratio of the sub-carrier frequency f_s to 1.023 MHz and n represents the ratio of the spreading code rate f_c to 1.023 MHz.

With the property of splitting spectrum, BOC modulation can reduce the intra-system interference and improve code delay tracking. Nevertheless, BOC-modulated signal will lead to a main drawback that is the autocorrelation function has multiple side-peaks, which will probably result in possible false acquisition. Several techniques have been proposed in the literature [2],[3].

The Sub Carrier Phase Cancellation (SCPC) method generates an in phase and quadrature sub carrier signals, getting rid of the sub carrier. Therefore, this method doubles the number of correlators because it is necessary for two channels wiping off the carrier to generate two kinds of sub carrier signal. The BPSK-like method receives upper sideband or lower sideband with local carrier frequency plus a subcarrier frequency or minus one. If only single sideband is received, it will bring some power loss. But the process of both sidebands will consume more correlators [4]. AsPeCT method combines two kinds of autocorrelation functions to formulate a new one. After that, the new autocorrelation function still has small side peaks. Also, it is only dedicated to sin-BOC (n,n) signals [5],[6].

Received January 26, 2015; Revised March 27, 2015; Accepted April 20, 2015

In this paper, we will focus on the acquisition of the sine-phased BOC*(kn,n)* signals, where k is the ratio of the sub-carrier frequency f_s to the spreading code rate f_c. At first, the signal model will be given. Then, two kinds of correlation functions are obtained which are composed of sub-correlations. Side peaks of auto correlation function will be shown. Through combining of different sub-correlations, we will have new correlation without side-peaks. Finally, theoretical results will be given.

2. Signal Model

The generic Binary Coded Symbols (BCS) ($[s_1, s_2, ...s_n]$, f_c) baseband signal can be expressed as [5]

$$s_{BCS}(t) = \sum_{i=0}^{n-1} (-1)^{s_i} p_{T_c/n}(t - \frac{iT_c}{n}) \quad (1)$$

where $s_i \in \{-1, 1\}$ is the i th chip of the binary sequence $[s_1, s_2, ...s_n]$, T_c is the PRN code chip period, $p_{T_c/n}(t)$ is a unit rectangular sub-carrier pulse waveform over $[0, T_c/n)$.

Sin-phased BOC baseband signal is a special case of (BCS) signal with a representation vector formed by +1's and -1's alternating in a particular defined way. The sine-phased BOC*(kn,n)* baseband signal can be expressed as

$$s(t) = \sum_{u=0}^{2k-1} (-1)^u p_{T_s}(t - iT_c - uT_s) \quad (2)$$

Where T_s is the sub-carrier pulse duration of $T_c / 2k = 1/(2kn \times 1.023MHz)$, $p_{T_s}(t)$ is the unit rectangular sub-carrier pulse waveform over [0, T_s). The full expression of sine-phased BOC*(kn,n)* signal will contain the spreading code and the navigation data, which is

$$s_{BOC_{sin}}(t) = \sqrt{P} \sum_{i=-\infty}^{\infty} c(t - iT_c) d(t - iT_c) s(t) \quad (3)$$

Where $c(t)$ is the spreading code and $d(t)$ is the navigation data. For the purpose of focusing on the ambiguous acquisition of $s_{BOC_{sin}}(t)$ signal, we assume that the navigation data is always 1, which means that we choose a pilot channel for acquisition and furthermore we also don't consider the effect of secondary code.

During the process of acquisition, the spreading code or the sub-carrier will be wiped off. Therefore, there are two kinds of autocorrelation function which depends on the local generated signal. One is the correlation of the sine-phased BOC*(kn,n)* with the spreading code only. The other is the correlation of the sine-phased BOC*(kn,n)* with the spreading code and sub-carrier both. Without considering the front-end filtering, the normalized BOC correlation function of the sine-phased BOC*(kn,n)* with the spreading code and sub-carrier both can be expressed as:

$$\begin{aligned} R_{SC}(\tau) &= \frac{1}{PT} \int_0^T s_{BOC_{sin}}(t) s_{BOC_{sin}}(t+\tau) dt \\ &= \frac{1}{PT} \sum_{m=0}^{T/T_c-1} \{[\sqrt{P} c(mT_c) \sum_{i=0}^{N-1} (-1)^i p_{T_s}(mT_c - iT_s)] \times [\sqrt{P} c(mT_c+\tau) \sum_{j=0}^{N-1} (-1)^j p_{T_s}(mT_c + \tau - jT_s)]\} \end{aligned} \quad (4)$$

$$
\begin{aligned}
&= \frac{1}{T}\sum_{m=0}^{T/T_c-1}\{c(mT_c)c(mT_c+\tau)[\sum_{i=0}^{N-1}(-1)^i p_{T_s}(mT_c-iT_s)\times\sum_{j=0}^{N-1}(-1)^j p_{T_s}(mT_c+\tau-jT_s)]\}\\
&= \frac{1}{T}\sum_{m=0}^{T/T_c-1}[\sum_{i=0}^{N-1}(-1)^i p_{T_s}(mT_c-iT_s)\times\sum_{j=0}^{N-1}(-1)^j p_{T_s}(mT_c+\tau-jT_s)]\\
&= \frac{T_s}{T_c}\sum_{i=0}^{N-1}\sum_{j=0}^{N-1}(-1)^{i+j}\Lambda_{T_s}(\tau-jT_s+iT_s)\\
&= \sum_{i=0}^{N-1}\frac{1}{N}\sum_{j=0}^{N-1}(-1)^{i+j}\Lambda_{T_s}(\tau-jT_s+iT_s)\\
&= \sum_{i=0}^{N-1}R_{SCsub}^{i}(\tau)
\end{aligned}
$$

Where

$$
\Lambda_{T_s}(\tau)=\begin{cases}1-\dfrac{|\tau|}{T_s}, & |\tau|\le T_s\\ 0, & |\tau|\ge T_s\end{cases} \tag{5}
$$

is a triangular function, which is the correlation function of two rectangular pulse waveform, and

$$
R_{SCsub}^{i}(\tau)=\frac{1}{N}\sum_{j=0}^{N-1}(-1)^{i+j}\Lambda_{T_s}(\tau-jT_s+iT_s) \tag{6}
$$

is the sub-correlation function of the sine-phased BOC*(kn,n)* with the spreading code and sub-carrier both. We can see that this sub-correlation function $R_{SCsub}^{i}(\tau)$ is a combination of triangular functions with different phases. And $R_{SC}(\tau)$ is the combination of different $R_{SCsub}^{i}(\tau)$, which is the reason of the ambiguity problem.

The second kind of correlation function is the correlation function of the sine-phased BOC*(kn,n)* with the spreading code only, which can be expressed as (7) in case that the front-end filtering is not considered.

$$
\begin{aligned}
R_C(\tau) &= \frac{1}{PT}\int_0^T s_{BOC_{sin}}(t)c(t+\tau)dt\\
&= \frac{1}{PT}\sum_{m=0}^{T/T_c-1}\{[\sqrt{P}c(mT_c)\sum_{i=0}^{N-1}(-1)^i p_{T_s}(mT_c-iT_s)]\times[\sqrt{P}c(mT_c+\tau)]\}\\
&= \frac{1}{T}\sum_{m=0}^{T/T_c-1}[c(mT_c)c(mT_c+\tau)\sum_{i=0}^{N-1}(-1)^i p_{T_s}(mT_c-iT_s)\times\sum_{j=0}^{N-1}p_{T_s}(mT_c+\tau-jT_s)]\\
&= \frac{1}{T}\sum_{m=0}^{T/T_c-1}[\sum_{i=0}^{N-1}(-1)^i p_{T_s}(mT_c-iT_s)\times\sum_{j=0}^{N-1}p_{T_s}(mT_c+\tau-jT_s)]\\
&= \frac{T_s}{T_c}\sum_{i=0}^{N-1}\sum_{j=0}^{N-1}(-1)^{i}\Lambda_{T_s}(\tau-jT_s+iT_s)\\
&= \sum_{i=0}^{N-1}\frac{1}{N}\sum_{j=0}^{N-1}(-1)^{i}\Lambda_{T_s}(\tau-jT_s+iT_s)\\
&= \sum_{i=0}^{N-1}R_{Csub}^{i}(\tau)
\end{aligned} \tag{7}
$$

Where

$$
R_{Csub}^{i}(\tau)=\frac{1}{N}\sum_{j=0}^{N-1}(-1)^{i}\Lambda_{T_s}(\tau-jT_s+iT_s) \tag{8}
$$

is the second kind of sub-correlation function, which is also the combination of triangular functions with different phases. However, the factor of triangular functions in two kinds of sub-correlation function is different. Two kinds of sub-correlation functions are shown in Figure 1.

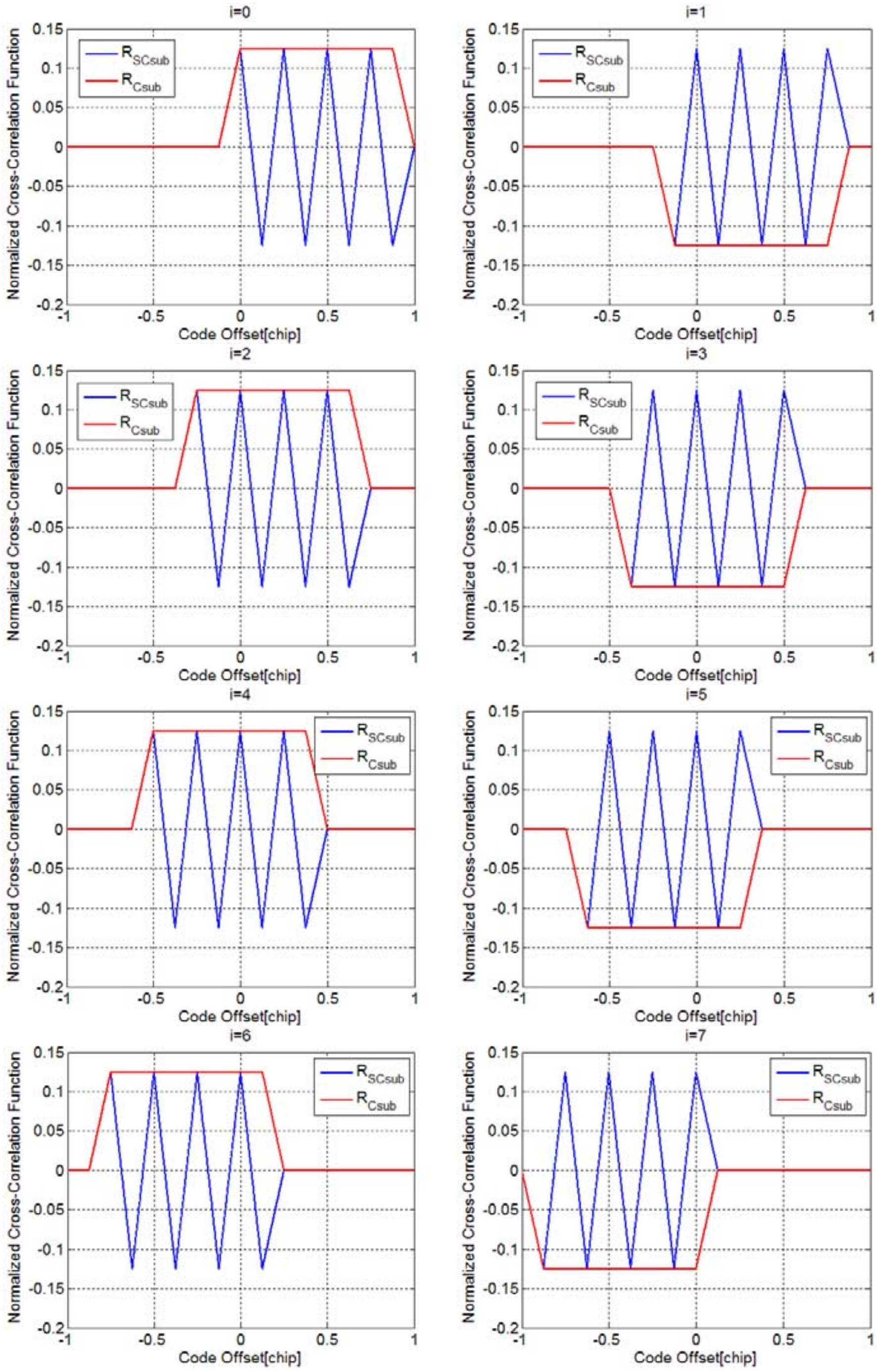

Figure 1. Correlation functions and sub-correlation functions

3. Proposed Method

From Figure 1, we can see that the first kind of sub-correlation function is composed of different side peaks both above zero and below zero. And the second kind of sub-correlation function is the envelope of the first kind of sub-correlation function, either above zero or below zero. When i is even, the second kind of sub-correlation is above zero and when i is odd, the second kind of sub-correlation is below zero. Therefore, the second kind of sub-correlation function can be used to make the first kind of sub-correlation function has only side peaks above zero. So we can get sub-correlation function only with side peaks above zero expressed as

$$R^i(t) = R^i_{SC}(t) + (-1)^i R^i_C(t) \tag{9}$$

When $i=0$, the left-most side peak of sub-correlation function is at $t=0$ and with i increased by 2, there will be one more side peak at $t < 0$ and one less side peak at $t > 0$. Finally, the right-most side peak of combined sub-correlation function is at $t=0$, when $i=N$. With the increase of i, the side peaks of different combined sub-correlation function move from the right of X-axis to the left and are symmetric about Y-axis, which can be expressed as

$$R^i(t) = R^{N-1-i}(-t) \tag{10}$$

We can just make use of this property to make sure that all of side peaks will be cancelled through combination of them. At first, we combine $R^0(t)$ and $R^{N-1}(t)$.

$$R_{com}(t) = [R^0(t) + R^{N-1}(t)] - \left|R^0(t) - R^{N-1}(t)\right| \tag{11}$$

And then, we can get the final correlation function by combining $R_{com}(t)$ with the sum of the combined sub-correlation functions, which can be expressed as

$$R_{final}(t) = R_{com}(t)\sum_{i=0}^{N-1} R^i(t) \tag{12}$$

4. Receiver Structure

Figure 2 shows the receiver structure of proposed method in this paper. The RF signal is first down-converted to IF signal. Then, the Doppler frequency is wiped off by the Local Code Generator. The output is multiplied by the local PRN code. There will be two channel to go on processing the signal. The aims of the two channel are to form the correlation of the sine-phased $\mathrm{BOC}(kn,n)$ with the spreading code and the subcarrier both and the correlation of the sine-phased $\mathrm{BOC}(kn,n)$ with the spreading code only. In one channel, the result will be integrated separately after multiplied by N different phases of local subcarrier, which is either '-1' or '+1'. All of the integrated result will be summed up and saved as one of R^i_{SCsub}. After the total coherent time T, there will be T/T_c R^i_{SCsub} and the sum of them will be the final R^i_{SCsub}. Finally, we will get N R^i_{SCsub}. In the other channel, the signal is processed almost the same. The only difference between them is that signal in the latter one will not be multiplied by local subcarrier and N of R^i_{Csub} will be got. And finally different R^i_{Csub} and R^i_{SCsub} will be combined to form the R_{final}. We can see that the sub-correlation function is got one by one sequentially. Therefore, compared with traditional method, no more correlators are needed in each channel.

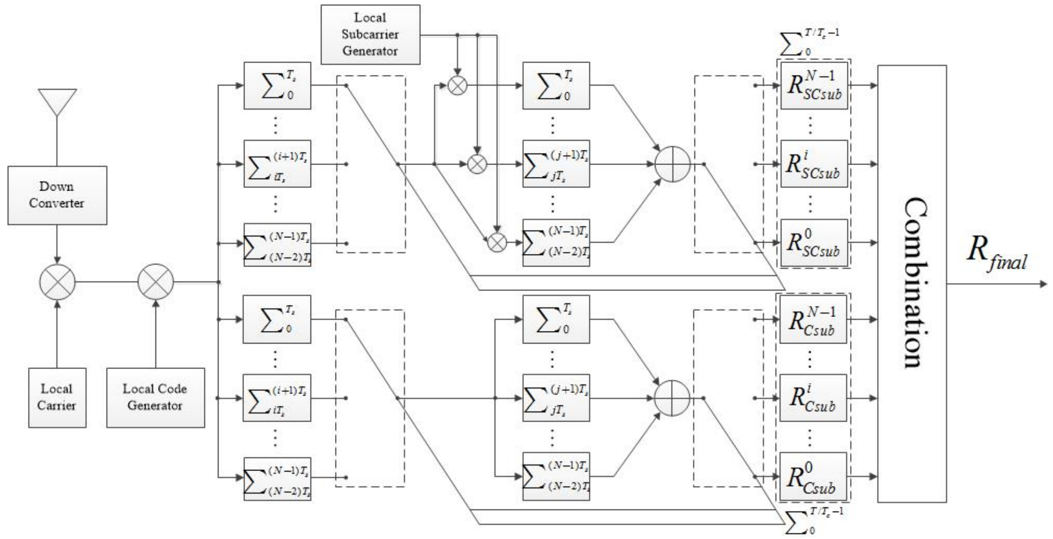

Figure 2. Receiver structure of the proposed method

It is shown that 2N of correlators works one by one. Only two of them are working at the same time. Therefore, we can make use of all of them to search different code phases at the same time. The architechture is shown as follow.

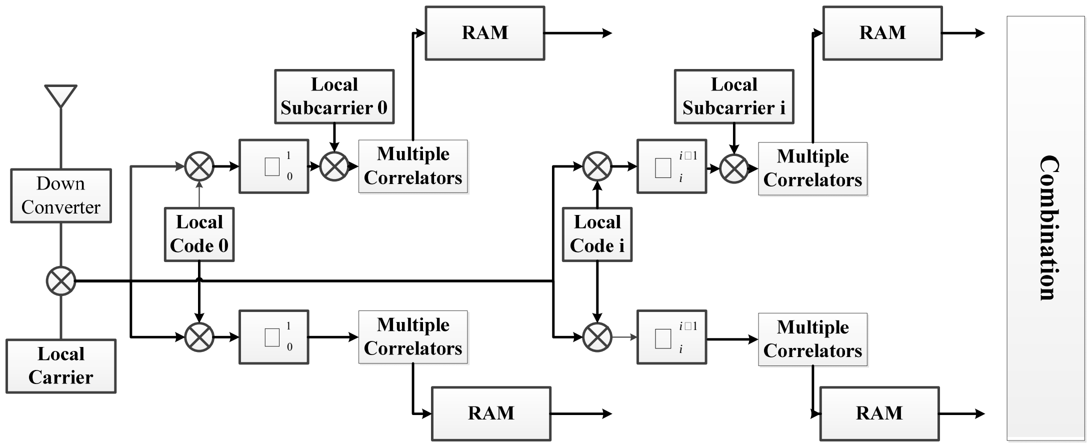

Figure 3. Time division receiver architechture of proposed method

Therefore, several correlation results can be got after coherent time. In this way, a faster acquisition will be accomplished.

5. Performance Analysis
5.1. Correlation Functions

For BOC(6n,n) signals, $N = 2k = 12$. There will be N, that is 12 sub-correlation functions. Figure 4 shows the sub-correlation functions, combined correlation function and final correlation function.

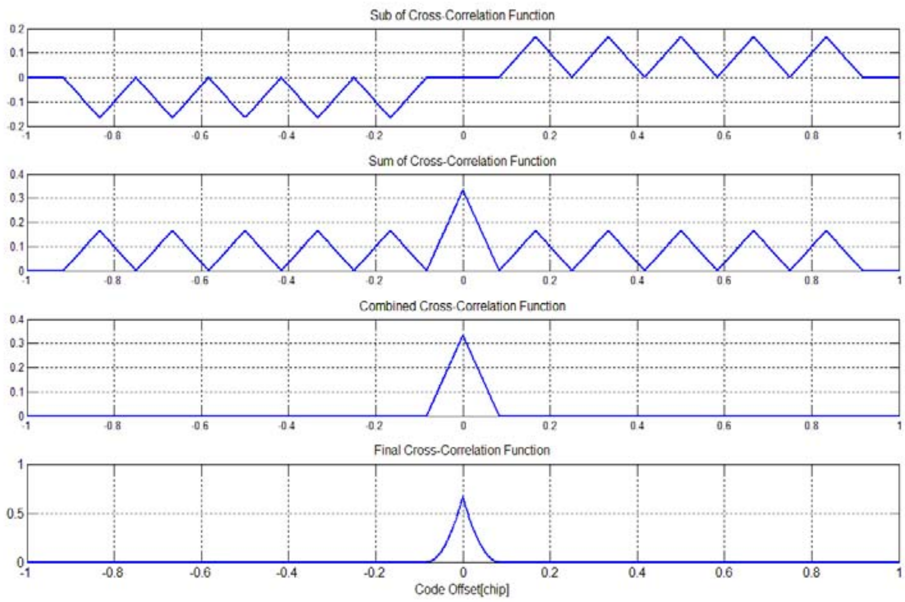

Figure 4. Correlation functions with k=6

5.2. Detection Probability

The goal of the acquisition process is to detect the presence of the useful signal and give a rough estimate of its main parameters including code delay and Doppler frequency. The theory of traditional acquisition method is widely developed and the expression of the correlator outputs can be expressed as

$$\begin{aligned} I(t,F_D) &= \frac{A}{2}R_{final}(t)sinc(\Delta f_e T_{coh})cos(\varphi)+n_I(t,F_D) \\ Q(t,F_D) &= \frac{A}{2}R_{final}(t)sinc(\Delta f_e T_{coh})sin(\varphi)+n_Q(t,F_D) \end{aligned} \quad (13)$$

Where $I(t,F_D)$ and $Q(t,F_D)$ are the correlator outputs with certain code delay and Doppler frequency, $A=\sqrt{P}$ is the received signal power, $R_{final}(t)$ is the final correlation function, Δf_e is the difference between the real Doppler frequency and the local Doppler frequency F_D, φ is the error on the phase, $n_I(t,F_D)$ and $n_Q(t,F_D)$ are the in-phase and quadrature correlator output noises. It is also proved that the noise coming from two channels to generate the sub-correlation function $R_{SC}^i(t)$ and $R_C^i(t)$ is independent and each of them is the Gaussian noise with a certain variance [7-9]. Combining them to formulate $n_I(t,F_D)$ and $n_Q(t,F_D)$ is a non-linear process, so it is difficult to obtain the mathematical expression of $n_I(t,F_D)$ and $n_Q(t,F_D)$.

In this paper, we choose Monte Carlo (MC) simulation with 10^4 runs to show the detection probability.

We assume the following parameters: $T_{coh}=LT_c=1ms$, $L=1023$, the code search step is T_s and false alarm is 10^{-4}. Furthermore, we assume that Doppler frequency is almost zero.

At first, we compare the BPSK-like technique and the proposed method. As shown in Figure 11, the proposed method performs better than the BPSK-like method when C/N0 is below 38 dB. And the BPSK-like method is a little better than the proposed method when C/N0 is between 39 dB and 42 dB.

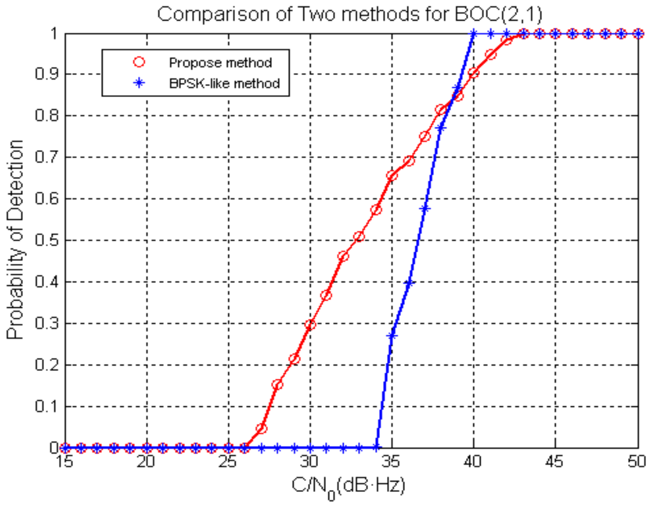

Figure 5. Comparison of two methods for BOC(2,1)

6. Conclusion

In this paper, a method to accomplish the side-peaks cancellation for unambiguous sine-phased BOC(kn,n) signal acquisition. First, we have introduced the signal model of the BOC (kn,n) signal and two kinds of correlation functions composed of several sub-correlation functions. Secondly, the method is proposed to cancel all of the side-peaks in the traditional correlation function and the final correlation function is formulated. Then, the final correlation functions with different k is shown. A time division receiver architechture is proposed also to accomplish a faster acquisition. Finally, detection probability of different BOC (kn,n) signals is compared by the Monte Carlo simulation. The proposed method is clearly observed to remove the side-peaks completely for the sine-phased BOC (kn,n) signal.

References

[1] Samad MF, Lohan ES. *MBOC Performance in Unambiguous Acquisition*. CDROM Proceedings of ENC-GNSS. 2009: 3-6.

[2] Martin N, Leblond V, Guillotel G, et al. *BOC (x, y) signal acquisition techniques and performances*. Proceedings of the 16th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS/GNSS 2003). 2001: 188-198.

[3] Xiao LZ, Yong G, Han CD. Design on the Timedomain Airborne Electromagnetic Weak Signal Data Acquisition System. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(1): 406-414.

[4] Heiries V, Roviras D, Ries L, et al. *Acquisition Performance Analysis of Candidate Designs for the L1 OS Optimized Signal.* Proceedings of the 16th Annual International Technical Meeting of the Satellite Division of the Institute of Navigation (ION)–Global Satellite Navigation System (GNSS). 2005.

[5] Julien O, Macabiau C, Cannon ME, et al. ASPeCT: Unambiguous sine-BOC (n,n) acquisition/tracking technique for navigation applications. *IEEE Transactions on Aerospace and Electronic Systems.* 2007; 43(1): 150-162.

[6] Avila RJA. *On generalized signal waveforms for satellite navigation*. Dept. Aerospace Engineer. University of Munich, Munich, Germany. 2008.

[7] Junxia C, Huli S. Satellite Communication and Navigation Integrated Signal. *TELKOMNIKA Indonesian Journal of Electrical Engineering.* 2013; 11(8): 4351-4356.

[8] Julien O, Cannon ME, Lachapelle G, et al. *A new unambiguous BOC (n, n) signal tracking technique*. Proceedings of The European Navigation Conference GNSS. 2004: 17-19.

[9] Zhong LD, Lu Y, Yue X, Zhong-wei Z, Hui D, Guan-yi W. Research on acquisition method of MBOC/Sideband AltBOC signals. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2014; 12(3): 2180-2188.