ICIC Express Letters
Part B: Applications
Volume **7**, Number **5**, May **2016**

ICIC International ©2016 ISSN 2185-2766
pp. 1013–1022

UNAMBIGUOUS GALILEO ACQUISITION USING BINARY PHASE-SHIFT KEYING-LIKE PARALLEL SHIFT-AND-COMBINE METHOD

Wei-Lung Mao[1,2,*], Suprapto[1], Chung-Wen Hung[1,2] and Ying-Ren Chien[3]

[1]Graduate School of Engineering Science and Technology
[2]Department of Electrical Engineering
National Yunlin University of Science and Technology
No. 123, University Road, Sec. 3, Douliou, Yunlin 64002, Taiwan
*Corresponding author: wlmao@yuntech.edu.tw; { d10210035; wenhung }@yuntech.edu.tw

[3]Department of Electrical Engineering
National Ilan University
No. 1, Sec. 1, Shen-Lung Road, Yilan 260, Taiwan
yrchien@niu.edu.tw

Received October 2015; accepted January 2016

Abstract. *Galileo will be Europe's own Global Navigation Satellite System (GNSS), which is aiming to provide highly accurate and guaranteed positioning services. Galileo E1 system has a code period of 4ms which is quadruple that of GPS C/A code. In other words, due to the large number of hypotheses in code phase at acquisition stage, a longer searching time or more hardware resource is required. It is difficult to acquire Galileo signal because of longer code length and the multiple peaks of autocorrelation function of BOC modulation. In this paper, the cyclically shift-and-combine (CSC) and BPSK-like architectures are employed to resolve the unambiguous acquisition for BOC modulation and acquire these satellite signals with hardware complexity reduction. The concept of CSC code is to modify the code structure and shorten the code period such that the acquisition burden can be decreased. Simulation results show that our proposed search algorithm can provide better performances in terms of low hardware complexity for acquiring these satellite signals and detection probability at the low value of carrier-to-noise density ratio (CNR).*
Keywords: Global Navigation Satellite System (GNSS), BOC modulation, Parallel BPSK (binary phase-shift keying)-like method, Cyclically shift-and-combine (CSC) method

1. **Introduction.** In 2004, the EU and U.S. make an agreement to establish a common baseline signal Binary Offset Carrier (BOC) [1,4,5] for the Galileo Open Service (OS) and the modernized civil GPS signal on the L1 frequency. The BOC modulation resulting split spectrum signal effectively enables frequency sharing, while providing attributes that include simple implementation, good spectral efficiency, high accuracy, and enhanced multipath resolution. However, BOC modulation brings some drawbacks for multiple peaks, which complicates signal acquisition process of miss-detection or wrong peak selection being higher. In order to avoid the ambiguities of the absolute value of ACF, the unambiguous BPSK-like algorithm, which can be seen as a superposition of two BPSK modulated signals, is employed to solve this difficulty. The CSC method is also presented to reduce the search space of code phases and acquisition computation complexities in this paper. There have been few studies on the Galileo satellite system design under distinct acquisition method environments. Several techniques are proposed to solve the problem caused by the BOC modulation problems [1,2]. However, the search space for Galileo signal is too complicated and time-consuming. The only method which can reduce the search complexity to the current references commonly used scheme is to

change the structure of its spreading code, such as the CSC [3]. Although the orthogonality of the modified code will not be as good as the original code, the modified CSC code can indeed correctly acquire the satellite and capture the code-phase information [3]. Also, the BPSK-like technique is used to eliminate the ambiguity of ACF for BOC signal modulation.

Once the acquisition process starts, the Doppler induced frequency offset of the received signal is compensated by a numerically controlled oscillator (NCO) with a preset Doppler bin. After the compensation process for the frequency offset is finished, the original spreading code is cyclically shifted by 1/4 of its length for four groups and then four groups cyclically shifted are combined or added to form a CSC code where the CSC code is original spreading code by half of its length. In this step, the band-pass filtered BOC signals with the BPSK-like architecture are correlated with CSC code stated above. Then, the parallel FFT/IFFT structures are utilized to perform the frequency domain correlation. If the testing statistic has passed the threshold test, the acquisition is finished and can be tried to enter the tracking process.

The remainder of this paper is organized as follows. In Section 2, Galileo received signal model is described. Section 3 proposes the Galileo acquisition CSC algorithm. The BPSK-like method is presented in Section 4. In Section 5, simulation results and analysis are demonstrated to verify the proposed methods. Section 6 concludes this paper.

2. **Galileo Signal Model.** The received Galileo E1B OS signal from a satellite of the Galileo system can be represented as [1,2]

$$\begin{aligned} y(t) &= y_{E1b}(t) + \eta(t) \\ &= A_i d_i(t-\tau_i)\, c_i(t-\tau_i)\, sc_i(t-\tau_i) \times \cos\left[2\pi\left(f_{E1b}+f_d\right)t + \varphi_i\right] + \eta(t) \end{aligned} \tag{1}$$

where A_i is the amplitude of the signal, $d_i(t)$ is the navigation data, and τ_i is the time delay. $c_i(t)$ is the Galileo E1b PRN code, and $sc_i(t)$ is the sub-carrier of the BOC signal. f_{E1b} and f_d are the E1b frequency and the Doppler shift, respectively. φ_i is the initial phase of the received signal, and $\eta(t)$ is additive white Gaussian noise with zero mean and the variance σ_{1F}^2. The received signal is band-pass filtered, amplified, and down-converted. Due to the frequency down-conversion, the spectrum of the signal is shifted to the intermediate frequency (IF).

3. **Galileo Signal Acquisition Method.** In this section, we are going to explain and analyze the CSC code in detail. Generating the CSC code consists of two procedures, which are cyclically shifted and combined. In the first step, the concept of "cyclically shift" is illustrated in Figure 1 where the original spreading code is cyclically shifted by half of its length. It is obvious that the shifted code is identical to the original spreading code except for the starting code phase. Second, the original spreading code and the shifted code are combined or added to form a new one. Finally the CSC code is derived by dividing the combined code into two parts with equal length and retaining the first one.

To verify the functionality of the CSC code, express the original spreading code of the i-th satellite as

$$x_i = \begin{bmatrix} x_{i,0} & x_{i,1} & \cdots & x_{i,N_c-1} \end{bmatrix}^T \tag{2}$$

where N_c is the code length and model the received signal of length N_c as

$$\begin{aligned} r &= \begin{bmatrix} r_0 & r_1 & \cdots & r_{N_c-1} \end{bmatrix}^T = x_{i,(n)N_c} \\ &= \begin{bmatrix} x_{i,(n)N_c} & x_{i,(n+1)N_c} & \cdots & x_{i,(n+N_c-1)N_c} \end{bmatrix}^T \quad 0 \le n \le N_c - 1 \end{aligned} \tag{3}$$

where n is the initial code phase of the received signal, $()_{N_c}$ is a modulo-N_c operation, and $x_{i,(n)N_c}$ is the representation of x_i cyclically shifted by n. For simplicity, it is assumed the received signal contains only the targeted satellite signal except for the initial code

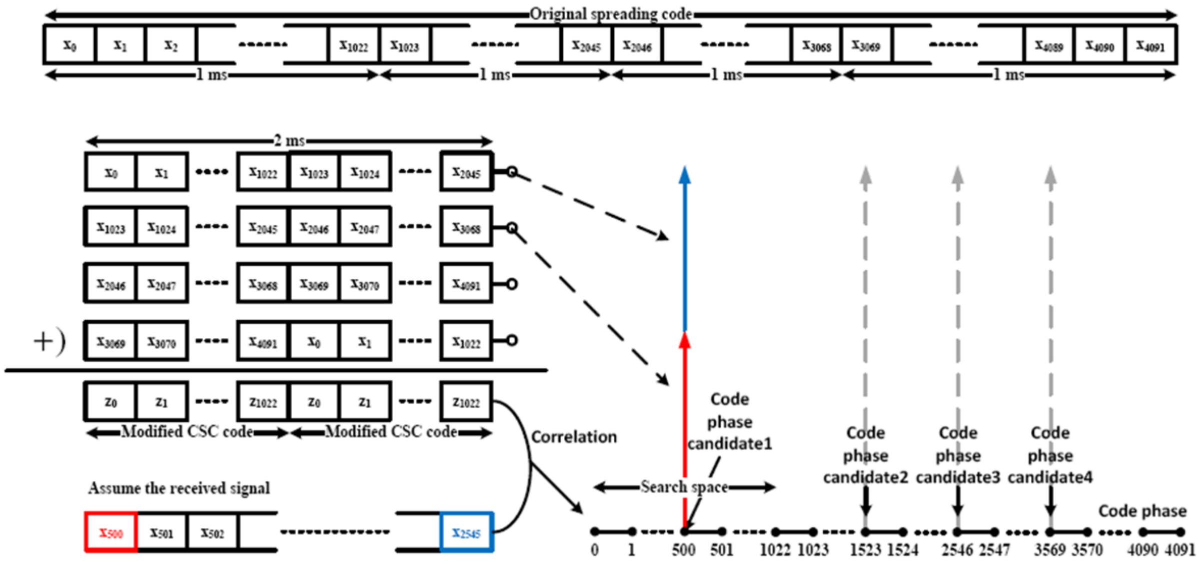


FIGURE 1. The modified CSC code generation for Galileo E1B signal

phase n, and the noise components were ignored. We define a full period correlation to be

$$U_{i,l} = x^T_{i,(l)_{N_c}} \cdot r = \sum_{k=0}^{\frac{N_c}{2}-1} x_{i,(l+k)_{N_c}} r_k + \sum_{k=N_c/2}^{N_c-1} x_{i,(l+k)_{N_c}} r_k = U_{i,l,1}+U_{i,l,2} \quad 0 \le l \le N_c-1, \tag{4}$$

with $U_{i,n} = U_{i,n,1} + U_{i,n,2}$, where $U_{i,l}$ is the correlation result between the received signal r and the local code replica x_i with a code-phase shift l. After the full period correlation is defined, the CSC code for the i-th satellite can be expressed as

$$y_i = \begin{bmatrix} y_{i,0} & y_{i,1} & \cdots & y_{i,N'_c-1} \end{bmatrix}^T = x_{i1} + x_{i2} \tag{5}$$

with $N'_c = N_c/2$

$$x_{i1} = \begin{bmatrix} x_{i,0} & x_{i,1} & \cdots & x_{i,\frac{N_c}{2}-1} \end{bmatrix}^T, \quad x_{i2} = \begin{bmatrix} x_{i,\frac{N_c}{2}} & x_{i,\frac{N_c}{2}+1} & \cdots & x_{i,N_c-1} \end{bmatrix}^T$$

We also define the CSC code correlation as

$$V_{i,l} = y^T_{i,(l)_{N'_c}} \cdot r_1 = \sum_{k=0}^{N'_c-1} y_{i,(l+k)_{N'_c}} r_k, \quad 0 \le l \le N'_c - 1, \tag{6}$$

with $r_1 = \begin{bmatrix} r_0 & r_1 & \cdots & r_{\frac{N_c}{2}-1} \end{bmatrix}$.

The vector r_1 is the first half of r. In the following, we will show no matter what the initial code phase n is, when the code synchronization is achieved, $V_{i,l}$ can always be expressed as

$$V_{i,l}\,|_{l=n} = U_{i,n,1} + I \tag{7}$$

where I is the aggregated interference term. All possible values of n can be classified into four groups as:

1) $n = 0$: In this case, $x_{i,1}$ is completely synchronized with r_1, but $x_{i,2}$ becomes the interference.

$$V_{i,l}\,|_{l=m} = y^T_{i,(0)_{N'_c}} \cdot r_1 = x^T_{i,1} \cdot r_1 + x^T_{i,2} \cdot r_1 = U_{i,n,1} + I \tag{8}$$

2) $n = N_c/2$: On the contrary, $x_{i,2}$ is now completely synchronized with r_1, but $x_{i,1}$ becomes the interference.

$$V_{i,l}\,|_{l=m} = y^T_{i,(N_c/2)_{N'_c}} \cdot r_1 = x^T_{2} \cdot r_1 + x^T_{i,1} \cdot r_1 = U_{i,n,1} + I \tag{9}$$

3) $0 < n < N_c/2$: Under this condition, a portion of both $x_{i,1}$ and $x_{i,2}$ contributes to the correlation result $U_{i,n,1}$.

$$\begin{aligned}
V_{i,l}\,|_{l=n} &= y^T_{i,(n)_{N'_c}} \cdot r_1 = \left(x^T_{i1,(n)_{N'_c}} + x^T_{i2,(n)_{N'_c}}\right) \cdot r_1 = \sum_{k=0}^{N'_c-1} \left(x_{i1,(n+k)_{N'_c}} + x_{i2,(n+k)_{N'_c}}\right) r_k \\
&= \left(\sum_{k=0}^{N'_c-n-1} x_{i1,(n+k)_{N'_c}} r_k + \sum_{k=N'_c-n}^{N'_c-1} x_{i1,(n+k)_{N'_c}} r_k\right) \\
&\quad + \left(\sum_{k=0}^{N'_c-n-1} x_{i2,(n+k)_{N'_c}} r_k + \sum_{k=N'_c-n}^{N'_c-1} x_{i2,(n+k)_{N'_c}} r_k\right) \\
&= (A+B)+(C+D) = \sum_{k=0}^{N'_c-1} x_{i,(n+k)_{N_c}} r_k + I = U_{i,n,1} + I
\end{aligned} \tag{10}$$

4) $N_c/2 < n < (N_c - 1)$: This case is very similar to 3) except that the contribution of correlation is from B and C as

$$V_{i,l}\,|_{l=n} = \sum_{k=N'_c-n}^{N'_c-1} x_{i1,(n+k)_{N'_c}} r_k + \sum_{k=0}^{N'_c-n-1} x_{i2,(n+k)_{N'_c}} r_k + (A+D) = U_{i,n,1} + I \tag{11}$$

From the above analysis, the initial code phase n of the incoming signal r can be detected by using the CSC code y_i although its code length N'_c does not span one complete period of the original spreading code. When the spreading code length is long like Galileo E1B/E1C, it is preferable to make the CSC code even shorter. Toward that, the described CSC code is modified so that its length is shorter than its predecessor. It is accomplished by cyclically shifting the original spreading code four times and combining them as demonstrated in Figure 1, where we see the code phases that required examination are only 1/4 of its original code length.

A generalized CSC code can be constructed as:

1) Cyclically shift the original spreading code L times such that the initial code phase of them is 0, N_c/L, $2N_c/L$, …, $(L-1)N_c/L$ chips, respectively. N_c is the length of the original spreading codes.

2) Combine and add all of these cyclically shifted codes.

3) Divide the combined code into L successive sections, and the first one is the CSC code with length $N'_c = N_c/L$.

4. **The BPSK-Like Method.** The BOC modulation presents a high degree of spectral separation from conventional signals. However, the corresponding acquisition method becomes more complicated. The BPSK-like method [1] consists in considering the received BOC(N, M) signal as the sum of two BPSK(M) signals with carrier frequency symmetrically positioned on each side of the BOC carrier frequency. Two correlation channel are generated and the corresponding filtered signals are placed at $f_{IF} + f_{sc}$ and $f_{IF} - f_{sc}$, respectively. The principle of this method is illustrated in Figure 2. Then the outputs of the digital accumulator become

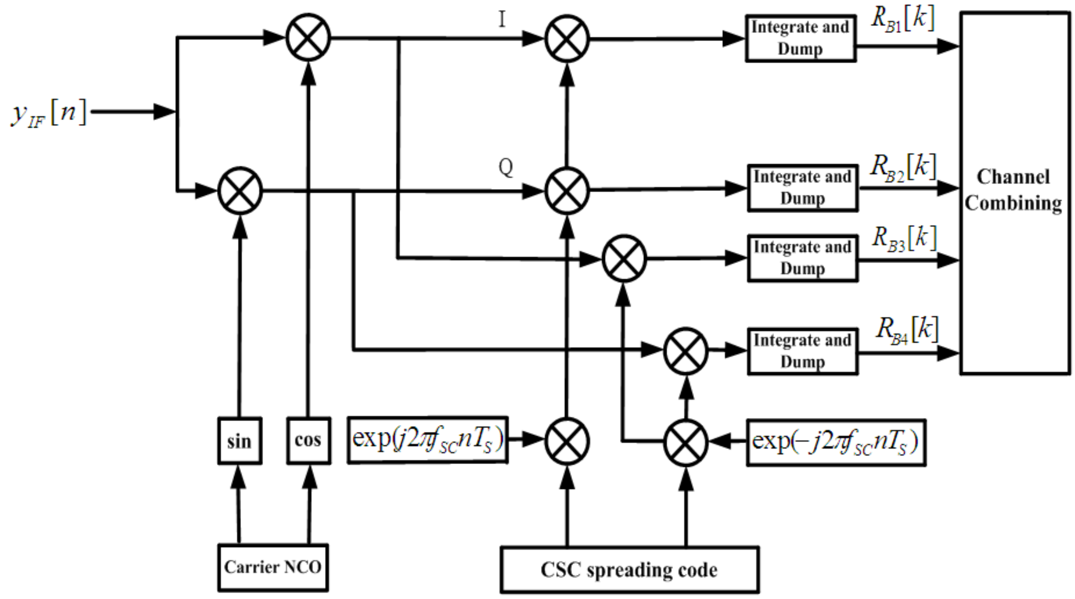
$$R_{B1}[k] = \frac{1}{\ell} \sum_{1=0}^{\ell-1} \{y_{1F}[n] H_1[n]\} = y_{1H}[k] + \eta_{1H}[k] \tag{12.1}$$

$$R_{B2}[k] = \frac{1}{\ell} \sum_{i=0}^{\ell-1} \{y_{1F}[n] H_Q[n]\} = y_{QH}[k] + \eta_{QH}[k] \tag{12.2}$$

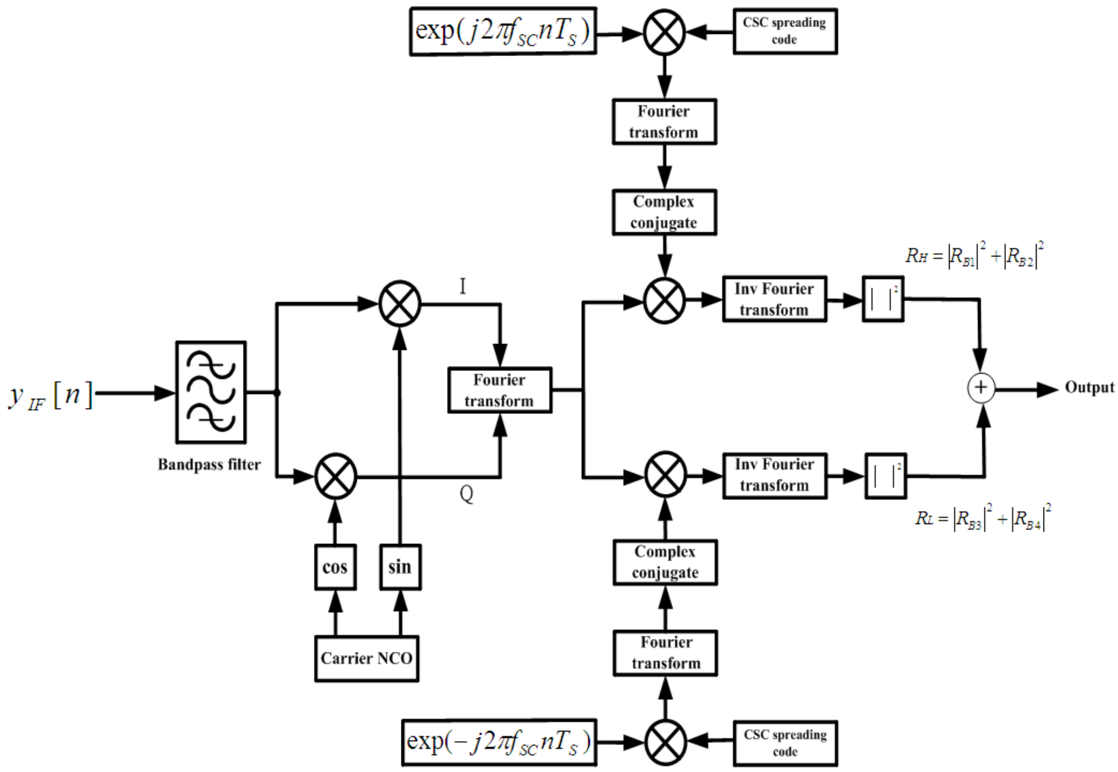
$$R_{B3}[k] = \frac{1}{\ell}\sum_{i=0}^{\ell-1}\{y_{1F}[n]L_1[n]\} = y_{1L}[k] + \eta_{1L}[k] \tag{12.3}$$

$$R_{B4}[k] = \frac{1}{\ell}\sum_{i=0}^{\ell-1}\{y_{1F}[n]L_Q[n]\} = y_{QL}[k] + \eta_{QL}[k] \tag{12.4}$$

where $\ell = T_C/T_S$ is the number of samples in coherent integration, and T_C is the coherent integration time. The integration and dump function blocks sum up their input signals



(a)



(b)

FIGURE 2. (a) Principle of time domain BPSK-like method, (b) principle of the frequency domain BPSK-like CSC

$y_{IF}[n]H_I[n]$ and $y_{IF}[n]H_Q[n]$ for I-phase and Q-phase channels, respectively. The final decision variable is obtained as

$$S = |R_{B1}[k]|^2 + |R_{B2}[k]|^2 + |R_{B3}[k]|^2 + |R_{B4}[k]|^2 \tag{13}$$

The parallel frequency domain method is developed such that it can achieve less computational burdens and simultaneously search multiple code phase process to speed up the acquisition. If $y_{IF}[n]$ is the Galileo received signal, then the correlation outputs for high-side frequency $R_H[m]$ and low-side frequency $R_L[m]$ can be represented as:

$$R_H[m] = \sum_{i=1}^{L} x[n]z[n]\exp(j2\pi f_{sc}nT_s) = x[n] \otimes [z[-n]\exp(-j2\pi f_{sc}nT_s)] \tag{14.1}$$

$$R_L[m] = \sum_{i=1}^{L} x[n]z[n]\exp(-j2\pi f_{sc}nT_s) = x[n] \otimes [z[-n]\exp(+j2\pi f_{sc}nT_s)] \tag{14.2}$$

with $x[n] = I(n) + jQ(n)$, $I(n) = y_{IF}(n)\cos[2\pi(f_{\mathrm{IF}} + f_d)nT_s + \varphi'_k]$, $Q(n) = y_{IF}(n)\sin[2\pi(f_{\mathrm{IF}} + f_d)nT_s + \varphi'_k]$, where $R_H[m]$ is the upper band correlation output, $R_L[m]$ is the lower band correlation output, $z[n]$ is the CSC code, and the operator $\otimes$ means the convolution operation. The final correlation decision output can be obtained as:

$$R[m] = R_H[m] + R_L[m] \tag{15}$$

where $R[m]$ is the combined correlation output for signal acquisition.

5. **Simulation Results.** In this section, MATLAB tool is used to evaluate the CSC method and BPSK-like structure for original E1b Galileo signal acquisition. The received intermediated frequency is set to 9.548 MHz. Assuming the frequency offset of the received satellite signal is located between ±5 kHz, the sample frequency is 38.192 MHz, the signal bandwidth is 8 MHz, and the frequency step during the Doppler search is set to be 125 Hz. The simulation results are ensemble-averaged over 100 independent Monte Carlo runs. The typical carrier-to-noise density ratio (CNR) [8] for the GPS receiver ranges from 35 to 55 dB-Hz and is defined by

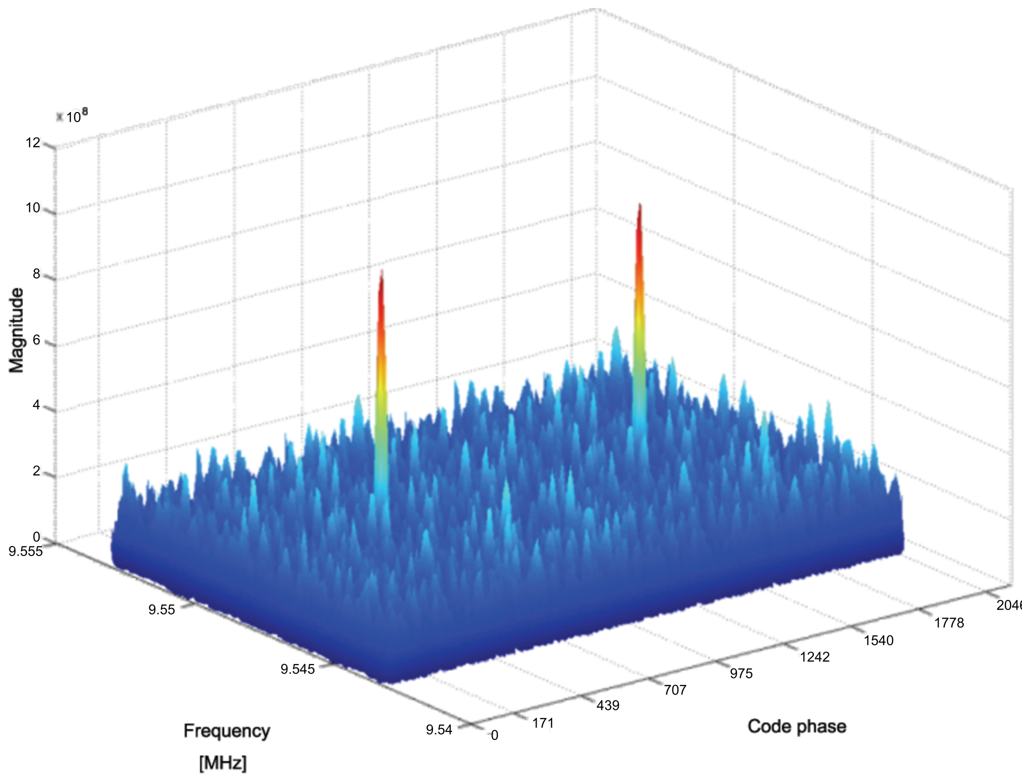
$$CNR = 10 * \log_{10}\{(SNR)(B)\} \text{ (dB-Hz)} \tag{16}$$

where SNR is the straight ratio form of the SNR at a certain point in the receiver, say, the final IF stage, and B is the bandwidth (in Hz) of that stage of the receiver.

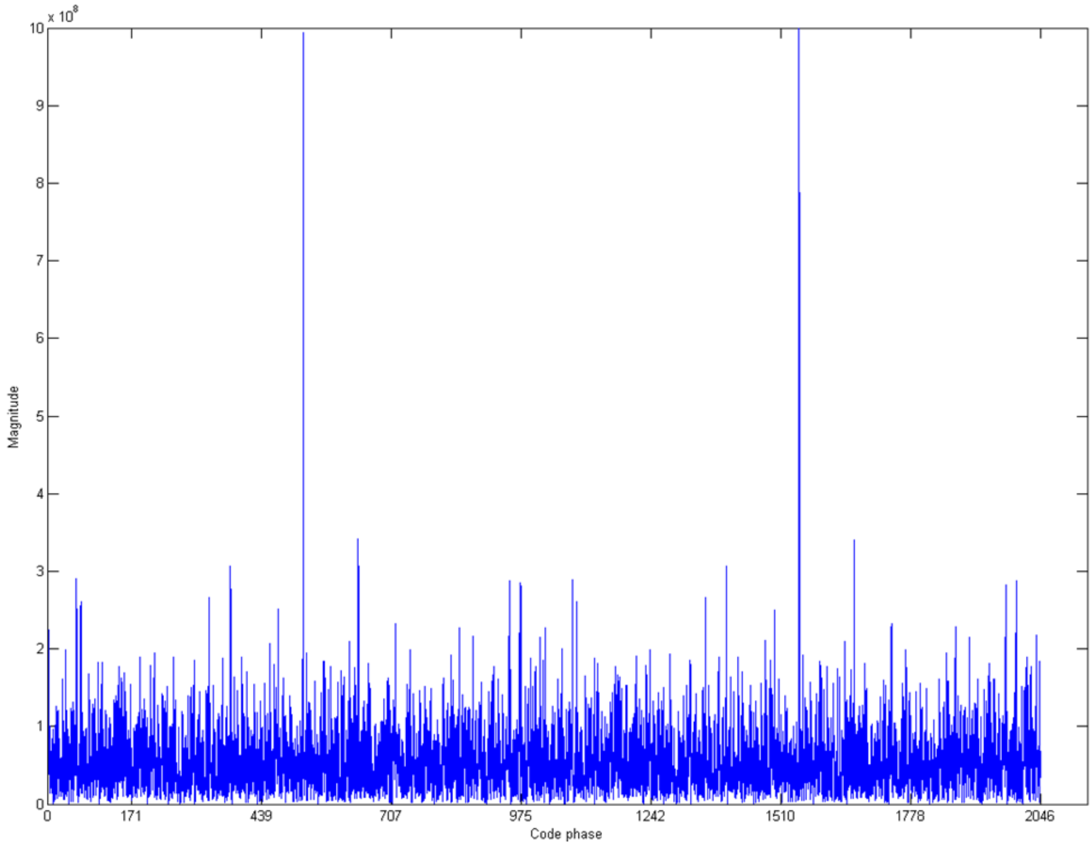
In Figure 3(a), it shows the two-dimensional autocorrelation function from the received Galileo signal and our proposed CSC method. The integration time is 2 ms and the SNR of all satellites are set as –20 dB, which represents an appropriate signal quality. In Figure 3(b), if the integration processing has been accomplished, the maximal peak out of 2 ms search results of code phases is compared to a detection threshold. The CSC method is applied here to determining the true code position between the two peaks in the correlation domain. However, if the maximum of them is larger than the threshold, the code phase and the Doppler frequency are fed into the tracking process, while the acquisition unit restarts to search another satellite signal.

Figure 4 shows the simulation-based histogram for correct and incorrect bins under different CNR environments. A test statistic is calculated in each search window according to the current correlation results. In this simulation, the distribution of the output is based on the chi-square random variable. In Figure 4(a) and Figure 4(b), the noise-only condition is central chi-square distribution, and the Galileo signal with noise is non-central chi-square distribution. In Figure 4(c), it can be observed that CSC method has a better performance under difference CNR. It is shown that the detection probability of CSC method is good enough for Galileo signal acquisition.

The simulations done here can assess the performance of our proposed CSC method and parallel BPSK-like method. Four architectures are compared; they are conventional

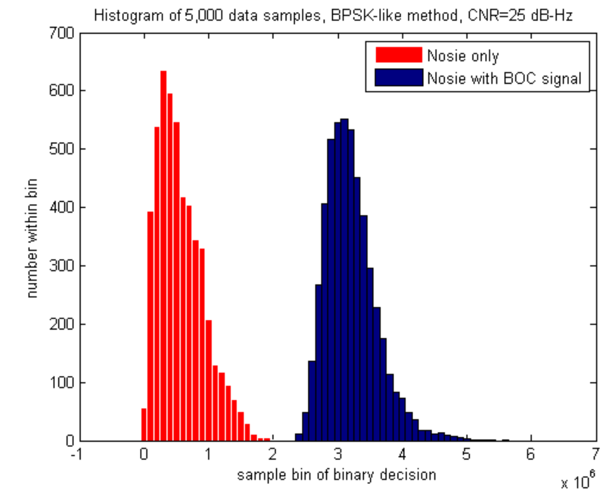


(a)

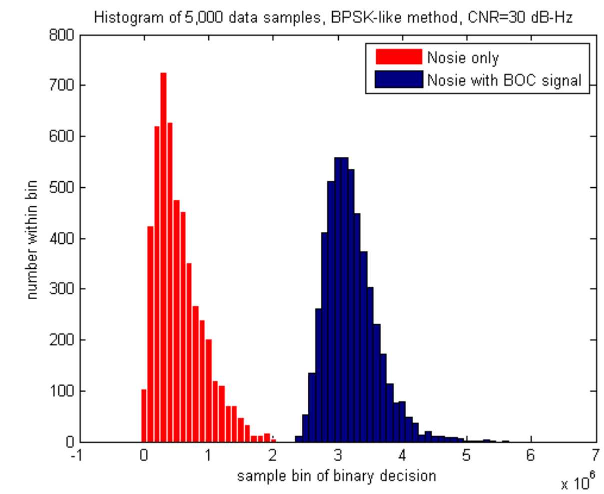


(b)

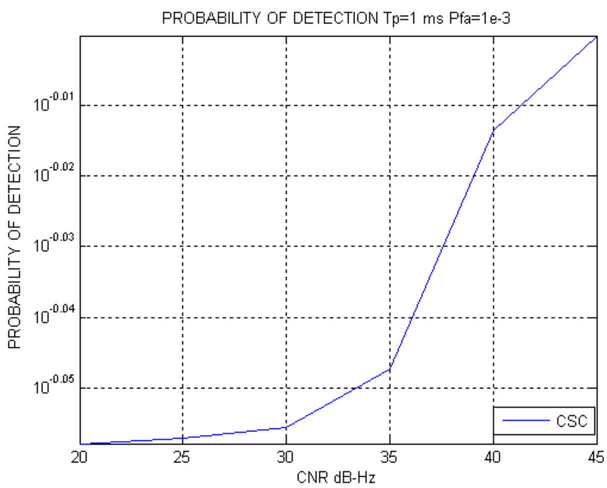
FIGURE 3. (a) The autocorrelation function of BPSK-like architecture, (b) the autocorrelation function at the zero Doppler frequency



(a)



(b)



(c)

FIGURE 4. The BPSK-like method acquisition performances: (a) CNR = 25 dB-Hz; (b) CNR = 30 dB-Hz; (c) probability of detection vs. CNR with CSC method

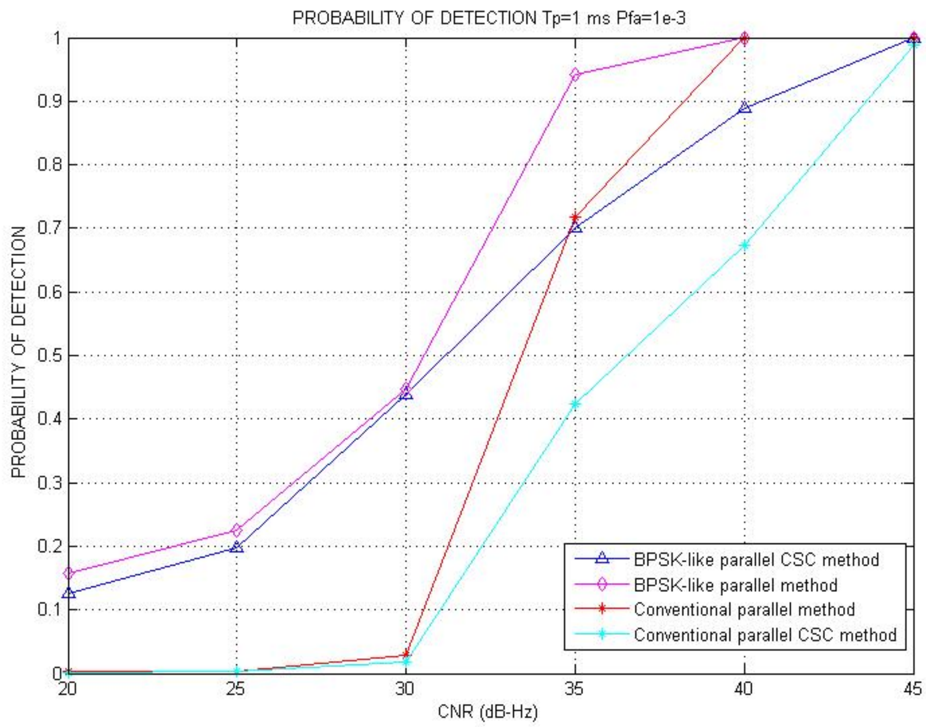


Figure 5. The detection probability for the four kinds of method

parallel method, BPSK-like parallel method, parallel CSC method, and BPSK-like parallel CSC method. Figure 5 shows the comparisons between these four architectures. It is shown that the BPSK-like method can provide a better performance than the conventional method under the same CNR conditions. By combining the parallel CSC code, the search space of the code phases shrinks and the corresponding computation burden of the code correlations can be reduced. While CNR is lower than 35 dB-Hz, the detection rate is better than the conventional parallel method. On the other hand, our BPSK-like parallel CSC code method provides a proper detection probability for high value of CNR, and can be utilized for unambiguous search in BOC modulation system.

6. **Conclusions.** In this paper, the unambiguous acquisition method using BPSK-like and CSC architecture has been evaluated for Galileo system. The CSC method can be used to reduce the complexity of search procedures, and its performance degradation in correlations has been evaluated. The BPSK-like search structure is used to yield the single correlation peak. Our proposed BPSK-like parallel CSC method can determine the exact phase of the satellite signal and reduce the computation burden. By using the statistical analysis, it shows that BPSK-like parallel CSC method provides the better detection rate than parallel method when CNR is lower than 35 dB-Hz. It also provides a suitable detection performance for higher CNR conditions. Based on the overall system we proposed, it aims to accomplish the shorter search time and better detection probability for Galileo satellite signal acquisition. Our method is planned to be developed and realized in software Galileo receiver.

Acknowledgment. This work was supported by the Ministry of Science and Technology of Taiwan. (MOST 103-2221-E-224-020-).

REFERENCES

[1] V. Heiries, D. Roviras, L. Ries and V. Calmettes, Analysis of non ambiguous BOC signal acquisition performance, *ION GNSS the 17th International Technical Meeting of the Satellite Division*, pp.21-24, 2004.

[2] Z. Yang, Z. Huang and S. Geng, Unambiguous acquisition performance analysis of BOC(m, n) signal, *International Conference on Information Engineering and Computer Science*, pp.1-4, 2009.

[3] P.-H. Lee, D.-H. Liu, W.-L. Mao, H.-W. Tsao and F.-R. Chang, A novel low-complexity acquisition method for next generation GNSS signals, *ION GNSS*, pp.1507-1513, 2008.

[4] M. F. Samad, *Effects of MBOC Modulation on GNSS Acquisition Stage*, Master Thesis, Tampere University of Technology, 2009.

[5] K. Borre, D. M. Akos, N. Bertelsen, P. Rinder and S. Jensen, *A Software-Defined GPS and Galileo Receiver*, 2007.

[6] D. Borio, *A Statistical Theory for GNSS Signal Acquisition*, Ph.D. Thesis, University of Politecnico di Torino, 2008.

[7] J. W. Betz, The offset carrier modulation for GPS modernization, *ION Technical Meeting*, 1999.

[8] M. S. Braasch and A. J. Van Dierendonck, GPS receiver architecture and measurement, *Proc. of the IEEE*, vol.87, no.1, pp.48-64, 1999.

[9] A. Rusa-Casandra, E. Lohan, G. Seco-Granados and I. Marghescu, Investigation of narrowband interference filtering algorithm for Galileo CBOC signals, *Proc. of European Conference of Communication*, pp.274-279, 2012.

[10] E. Lohan and G. Seco-Grandados, C/N-0-based criterion for selecting BOC-modulated GNSS signals in cognitive positioning, *IEEE Communication Letters*, vol.17, no.3, pp.537-540, 2013.