An Unambiguous Deterministic Compressed Acquisition Technique for BOC Signal

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Abstract

The long PN code in a Binary Offset Carrier (BOC) modulated signal has a higher rate than the GPS C/A code, which makes the acquisition process in the new global navigation satellite system (GNSS) much more complex. To achieve a fast acquisition of the GNSS signal with a reduced number of correlators and low computational complexity, a two-stage deterministic compressed (DS) GNSS acquisition technique has been proposed. Nevertheless, the ambiguous threat of BOC signal isn't taken into account in the DS technique. To eliminate the ambiguity threat in the acquisition process of BOC (m, n) signal, an unambiguous deterministic compressed acquisition is proposed in this paper. The main idea of the proposed technique is to introduce a simplified GRASS algorithm in the second stage measurement. Theoretical analysis and simulation results show that, at the expense of some performance degradation the proposed technique can completely remove the undesired positive side peaks of BOC (m, n) signal, and reduce the chance of false peak acquisition compared with the DS technique.

Keywords: Binary offset carrier (BOC), global navigation satellite system (GNSS), unambiguous acquisition, deterministic compressed

1. Introduction

With the advent of the new global navigation satellite system, split-spectrum type modulated signals, such as binary offset carrier (BOC) signals, have been adopted in the next-generation GNSS to provide a better spectral separation between the existing GNSS systems such as modernized GPS, Galileo, GLONASS and COMPASS. A BOC signal is defined as a spreading pseudo random noise (PRN) code modulated by a square-wave subcarrier, and it's denoted as $\text{BOC}(f_{sc}, f_c)$ or $\text{BOC}(m, n)$, where $f_{sc} = m \times 1.023\text{MHz}$ is the subcarrier frequency and $f_c = n \times 1.023\text{MHz}$ is the chip rate[1]. Since the square wave subcarrier can either be sine or cosine phased, the BOC signal is usually denoted as $\text{BOCs}(m, n)$ and $\text{BOCc}(m, n)$. It has been revealed that BOC modulation can improve the code tracking performance and provide the advantages of multipath effect reduction and narrow band interference rejection [2]. However, the PRN code in BOC modulation signal has a much higher chip rate than the one in a GPS C/A signal, for which a receiver should have a higher search resolution, and the acquisition process has increased complexity [3]. Additionally, the existence of subcarrier in a BOC signal induces side peaks on both side of the center peak of the autocorrelation function (ACF), which may bring ambiguity threat in acquisition and tracking processes under multipath and interference environment.

Since the acquisition process for a BOC signal requires elaborate work, many methods have been proposed to solve this problem [4-10]. Serial search tests all code phases one-by-one, which makes a very long search process [4]. On the contrary Parallel-correlator-based technique completes the acquisition by testing the phase of every PRN code in

parallel, which needs multiple times in number of parallel correlators than the GPS C/A code [5]. The fast Fourier transform (FFT)-based technique uses a digital signal processor for fast computation, but it requires much more complex multiplications than the traditional method [6]. Folding technique and dual folding technique [8, 9] provide another valid approach to accelerate the acquisition process by folding local signal and the incoming signal, and in this method the code phases to be searched will be decreased proportional to the folding number, but it suffers from SNR degradation with the increase of folding number. A two-stage deterministic compressed GNSS acquisition technique has been proposed to reach a good compromise between the correlator number and the acquisition time [10]. But the authors in [10] only discussed the performance of this method when used on GPS signal and BOC (n, n) signal, and both the transform matrix and the measurement matrix are not suitable for BOC (m, n) signal, besides, the ambiguity threat was not taken into account.

In this paper, we improve the deterministic compressed GNSS acquisition technique by introducing new transform matrix and measurement matrix, and adding an improved GRASS technique in the second stage. The proposed technique is suitable for all BOC signal and the ambiguity threat is suppressed at the same time. We first describe the proposed technique for different BOC modulations, and then the performances of the proposed technique are analyzed. Next a comparison of the proposed technique to other techniques is discussed. Lastly the conclusions are given.

2. Description of the Proposed Method

The incoming BOC (m, n) signal in a GNSS receiver can be expressed as:

$$r(t) = \sqrt{2PD}(t-\tau)C(t-\tau)sc(t-\tau)e^{j(2\pi(f_{IF}+f_D)t+\varphi)} + n(t) \quad (1)$$

where P , τ , f_{IF} , f_D and φ are the power, code delay, IF carrier frequency, Doppler frequency, and carrier phase of the received signal, respectively. $D(t)$ and $n(t)$ represent the navigation data at the rate of R_b bps and the incoming Gaussian noise with two-side power spectral density $N_0/2$, respectively. $P(t)$ is the spreading sequence at code frequency $f_c = n \times 1.023 \text{ MHz}$, $sc(t)$ is the subcarrier, and its mathematical representation is represented as

$$sc(t) = \begin{cases} \text{sgn}(\sin(2\pi f_{sc}t)), & \text{for sin BOC} \\ \text{sgn}(\cos(2\pi f_{sc}t)), & \text{for cos BOC} \end{cases} \quad (2)$$

where $f_{sc} = m \times 1.023 \text{ MHz}$ is the subcarrier frequency. $\alpha = 2m/n$ is the modulation order which is a positive integer. In practice, GNSS signal search is a 2-Dimensional hypothesis testing, which will search both code phase and the Doppler frequency of the received signal. During the acquisition process, the receiver multiplies the received signal by $e^{-j2\pi(f_{IF}+f_d+p\Delta f)t}$ to remove the carrier frequency, where f_d is the minimum Doppler frequency estimated by the receiver, Δf is the frequency search step size, and $p(p=0,1,2,\dots,p_{\max})$ is the Doppler frequency index.

To keep the better precision in the estimation of the delay and phase for the incoming BOC signal, we choose a sampling frequency $f_s = \alpha f_c$, and the sampled received signal can be expressed as $\mathbf{r} = \{r[0], r[1], \dots, r[\alpha L - 1]\}^T$, where $L=1023$ is the code length of the PN code. As the BOC signal has a very sparse expression in the autocorrelation output, we can get the transform matrix Ψ :

$$\psi_{l,k} = B[\lceil (k-l)T_s f_c \rceil (\text{mod } L)] \quad (3)$$

where $B(t) = C(t)sc(t)$, $l, k \in \{0, 1, 2, \dots, \alpha L - 1\}$. When $f_d + p\Delta f$ is closed enough to f_D , we can turn the received BOC signal into its sparse domain by multiplying it by the transform matrix Ψ ,

$$\mathbf{R} = \Psi \mathbf{r} \quad (4)$$

where $\mathbf{R}$ is a K -sparse signal with $K = 2\alpha - 1$ that represents all code phases in $1/\alpha$ -chip resolution. The amplitude of $\mathbf{R}$ can be thought as the ACF of BOC (m, n) signal. We use $\mathbf{R}_B$ to represent the normalized ACF of BOC signal without noise [2]:

$$R_B(\tau) = \begin{cases} (-1)^{k+1} \left[\frac{\tau(2\alpha - 2k - 1)}{T_c} - \frac{2(\alpha - 1)k - 2k^2 + \alpha}{\alpha} \right], & \frac{kT_c}{\alpha} \leq \tau < \frac{(k+1)T_c}{\alpha} \\ (-1)^{k+1} \left[\frac{\tau(2k - 1)}{T_c} + \frac{(\alpha - k)(2k - 1) - k}{\alpha} \right], & \frac{(k - \alpha)T_c}{\alpha} \leq \tau < \frac{(k - \alpha + 1)T_c}{\alpha} \\ 0, & |\tau| > T \end{cases} \quad (5)$$

where $k = \{0, 1, \dots, \alpha - 1\}$. Fig.1 shows the normalized ACF of the BOC(2n,n) signal and BOC(n,n) signal, it's obviously that the number of side peaks becomes larger as the value of α increases

Figure 1. The Envelop of BOC (2n, n) and BOC (n, n) Signal Autocorrelation Functions

In this paper, the proposed technique is divided into two stages.

A. 1st-Stage

The first stage measurement is the same as the one in [10]:

$$\mathbf{y}_1 = \Phi_1 \mathbf{R} = \Phi_1 \Psi \mathbf{r} \quad (6)$$

where, the element of measurement matrix Φ_1 can be defined as

$$\phi_{l_{m,l}} = \frac{(-1)^l}{\sqrt{M_1}} \mathbf{W}_{M_{01}} \left[m, \left\lceil \frac{l}{\eta} \right\rceil \right] \quad (7)$$

where $1 \leq m \leq M_1, 1 \leq l \leq \alpha L$, $\mathbf{W}_{M_{01}}$ is a Walsh-Hadamard matrix of size $[M_1 \times M_1]$, $M_1 = 2^{M_{01}}$, η is called compression ratio, which satisfies $\eta M_1 \square \alpha L$.

The first stage measurement can be implemented by the following steps:

Step1. Multiplying the sampled received signal $\mathbf{r}$ by the transform matrix Ψ to get $\mathbf{R}$:

$$\mathbf{R} = \Psi \mathbf{r}.$$

Step2. Multiplying $\mathbf{R}$ by the measurement matrix Φ_1 to get the observed signal $\mathbf{y}_1$:

$$\mathbf{y}_1 = \Phi_1 \mathbf{R} = \Phi_1 \Psi \mathbf{r}.$$

Step3. Calculating the FWHT transform of $\mathbf{y}_1$:

$$\mathbf{Z}_1 = |\mathbf{z}_1|^2 = |M_1 - \text{point FWHT of } \mathbf{y}_1|^2.$$

Step4. Selecting maximum N_p largest elements of $\mathbf{Z}_1$, which must be larger than the first-stage detection threshold γ_1 at the same time, and let $\mathbf{w}_1$ denote the index of the selected element:

$$\mathbf{w}_1 = \arg \left\{ \left\{ N_p \text{ largest elements of } \mathbf{Z}_1 \right\} \cap \left\{ \mathbf{Z}_1 \geq \gamma_1 \right\} \right\}.$$

Step5. If $\|\mathbf{w}_1\|_0 > 0$, proceed to the 2nd-stage with $\mathbf{W}_1$:

$$\mathbf{W}_1 = \bigcup_{w_1 \in \mathbf{w}_1} \left\{ \eta w_1 + 1, \eta w_1 + 2, \dots, \min \{ \eta(w_1 + 1) + 1, \alpha L \} \right\},$$

Otherwise, repeat 1st-stage with $p = p + 1$.

During the first stage measurement, $z_1 \in \mathbf{z}_1$ can be expressed as:

$$z_1(m) = \sum_{n=\eta(m-1)+1}^K R(n) \quad (8)$$

where $0 \leq m \leq M_1$, $K = \min \{ \eta m, \alpha L \}$, thus it can be considered that the first stage measurement completes the signal compression by adding every η elements of $\mathbf{r}$. The code phases to be searched are directly decreased proportional to η .

A. 2nd-Stage

According to the previous introduction, the ACF of BOC signal has multi peaks which may bring an ambiguity threat in signal acquisition and tracking. To get rid of this problem, we apply the improved GRASS technique in the second stage measurement of the proposed technique.

BOC signal can be considered as a special case of step-shape code symbol (SCS) signals whose shape vector is $\mathbf{d}_B = [1, -1, \dots, 1, -1]_{\alpha \times 1}^T$. Thus we can get any BOC signal by multiplying each chip of the PN code by corresponding $\mathbf{d}_B$. In this stage, a new synthetic ACF $\mathbf{R}'$, is applied to accomplish the acquisition process:

$$\mathbf{R}'_B = \mathbf{R}_B^2 - \beta \mathbf{R}_{B/L}^2 \quad (9)$$

where, $\beta = 2\alpha - 3$, $\mathbf{R}_{B/L} = \Psi_L \mathbf{r}$, $\psi_{L,k} = L \left[\left[(k-l)T_s f_c \right] (\text{mod } L) \right]$ and $L(t)$ is the local SCS signal whose shape vector $\mathbf{d}_L = [d_0, d_1, \dots, d_{\alpha-1}]_{\alpha \times 1}^T$,

$$\begin{cases} d_0 = d_{\alpha-1} = \frac{\alpha-1}{\sqrt{2\alpha-3}} \\ d_i = d_{\alpha-i-1} = \frac{(-1)^{i-1}}{\sqrt{2\alpha-3}}, \left(i = 1, 2, \dots, \frac{\alpha}{2} - 1 \right) \end{cases} \quad (10)$$

According to the description above, we can get Ψ_L easily by doing some calculations of Ψ : $\psi_{L,k} = \psi_{l,k} d_k$, where $d_k \in \mathbf{d} = [\mathbf{d}_B^T \bullet \mathbf{d}_L^T \mathbf{d}_B^T \bullet \mathbf{d}_L^T \dots \mathbf{d}_B^T \bullet \mathbf{d}_L^T]_{1 \times \alpha L}^T$. The second stage measurement of the proposed method can be implemented by the following steps:

Step1. Let M_{02} equal $\lceil \log_2 \|\mathbf{W}_1\|_0 \rceil$, ν be the index of elements of $\mathbf{W}_1$, and generate another Walsh-Hadamard matrix $\mathbf{W}_{M_{02}}$ with the size of $[M_2 \times M_2]$, where $M_2 = 2^{M_{02}}$.

Step2. Generate $\mathbf{R}_2$ and the measurement matrix Φ_2 :

$$R'_{m,\nu} = \mathbf{R}^2(l) - \beta \mathbf{R}_{B/L}^2, \Phi_2 = \mathbf{W}_{M_{02}} / \sqrt{M_2},$$

where $\nu = \{1, 2, \dots, \|\mathbf{W}_1\|_0\}$, $\nu = \{1, 2, \dots, \|\mathbf{W}_1\|_0\}$, $R_{2m,\nu}$ is the element of $\mathbf{R}_2$, $\mathbf{R}_2 \in \mathbb{R}^{M_2 \times M_2}$, $R(l)$, $R_{B/L}(l)$ is the l th element of $\mathbf{R}$ and $\mathbf{R}_{B/L}$.

Step3. Get the observed signal $\mathbf{y}_2$:

$$\mathbf{y}_2 = \Phi_2 \mathbf{R}'.$$

Step4. Calculating the FWHT transform of $\mathbf{y}_2$:

$$\mathbf{Z}_2 = \{M_2 - \text{point FWHT of } \mathbf{y}_2\}.$$

Step5. Finding the index of the largest element in $\mathbf{Z}_2$, which is larger than the second-stage detection threshold γ_2 :

$$\mathbf{w}_2 = \arg \{ \{ \text{largest element of } \mathbf{Z}_2 \} \cap \{ \mathbf{Z}_2 \geq \gamma_2 \} \}.$$

Step6. If $\|\mathbf{w}_2\|_0 > 0$, return $\|\mathbf{w}_2\|_0 > 0$, and the acquisition process is accomplished, otherwise, repeat 1st-stage with $p = p + 1$.

The method used in the second stage of the proposed technique is not the same as the GRASS technique. After the first stage measurement, the phase search range has been reduced from αL to $\|\mathbf{W}_1\|_0$, thus we just need calculate $\|\mathbf{W}_1\|_0$ elements of $\mathbf{R}'$ and Ψ_L here instead of αL elements in GRASS. Compared with the GRASS, the proposed technique needs much less computation and hard resources.

3. Performance Analysis

To analyze the performance of the proposed technique, in this section, we calculate the detection and false alarm probabilities. Here we assume $N_p = 1$ as the simplest implementation of the proposed technique, and the incoming noise is Gaussian noise. For the first stage measurement, when there is no signal present, the distribution of $Z_1 \in \mathbf{Z}_1$ is a central chi-square distribution with two degrees of freedom, the probability distribution function of Z_1 can be expressed as:

$$p_{fa1}(Z_1) = \frac{1}{2\sigma_1^2} \exp\left(-\frac{Z_1}{2\sigma_1^2}\right) \quad (11)$$

where $\sigma_1^2 = (2\eta - 1)\alpha L N_0 / 2$. We can get the false alarm probability of each test cell according to the definition of false alarm probability.

$$P_{cell,fa1} = \int_{\gamma_1}^{\infty} p_{fa1}(Z_1) dZ_1 = \exp\left(-\frac{\gamma_1}{2\sigma_1^2}\right) \quad (12)$$

The overall false alarm probability is:

$$P_{fa1} = 1 - [1 - P_{cell,fa1}]^{M_1} \approx M_1 P_{cell,fa1} \quad (13)$$

For signal present case, the distribution of $Z_1 \in \mathbf{Z}_1$ is a noncentral chi-square distribution with two degrees of freedom, the PDF of Z_1 can be expressed as:

$$p_{d1}(Z_1) = \frac{1}{2} \exp\left(-\frac{\lambda_1}{2}\right) \exp\left(-\frac{Z_1}{2\sigma_1^2}\right) \sum_{m=0}^{\infty} \frac{\left(\frac{\alpha}{\sigma_1^2}\right)^m \lambda^m}{\Gamma\left(\frac{1}{2} + m\right) 2^{2m} m!} \quad (14)$$

where $\lambda = S_1^2 / \sigma_1^2$. The signal amplitude S_1 in the first stage measurement can be expressed as:

$$S_1 = \begin{cases} \alpha \sqrt{2PL} \sum_{i=0}^{\eta-1} R_B \left((i+1 - (l_T \pmod{\eta})) \frac{T_c}{\alpha} \right), & l_T \pmod{\eta} \neq 0 \\ \alpha \sqrt{2PL} \sum_{i=0}^{\eta-1} R_B \left(\frac{iT_c}{\alpha} \right), & l_T \pmod{\eta} = 0 \end{cases} \quad (15)$$

where $l_T (1 \leq l_T \leq \alpha L)$ is the index of the maximum peak in $\mathbf{R}$. For BOC(n, n) signal when $\eta > 3$, $\bar{S}_1 = \left(2 - \frac{1}{\eta}\right) 2\sqrt{2PL}$; for BOC(2n, n) signal when $\eta > 7$, $\bar{S}_1 = \left(4 - \frac{4}{\eta}\right) 4\sqrt{2PL}$.

The detection probability is defined as:

$$P_D = \int_{v_T}^{\infty} p_d(x) dx \quad (16)$$

Then we can establish the detection probability of the proposed technique by applying (14) in (16), the detection probability of the first measurement can be expressed as [10]:

$$P_{D1} \geq \sum_{n=0}^{M_1-1} \frac{(-1)^n}{n+1} \binom{M_1-1}{n} \exp\left(-\frac{nS_1^2}{2(n+1)\sigma_1^2}\right) \times Q\left(\sqrt{\frac{2S_1^2}{2(n+1)\sigma_1^2}}, \sqrt{\frac{2(n+1)\gamma_1}{2\sigma_1^2}}\right) \quad (17)$$

For the second stage measurement, we use the improved GRASS technique to eliminate the ambiguity threat. When there is no signal present, both of the first term and the second term in (9) follow central chi-square distribution with two degrees of freedom, but with different variances $\sigma_{2,1}^2 = \alpha LN_0 / 2$, $\sigma_{2,2}^2 = \beta \sigma_{2,1}^2 = \beta \alpha LN_0 / 2$. Then we can give the false alarm probability of each test point in the second term expression by exploiting the derivations in [2]:

$$P_{cell,fa2} = \frac{1}{1+\beta} \exp\left(-\frac{\gamma_2}{\alpha LN_0}\right) \quad (18)$$

The overall false alarm probability is:

$$P_{fa2} = 1 - [1 - P_{cell,fa2}]^{M_2} \approx M_2 P_{cell,fa2} \quad (19)$$

For signal present case, when the code delay is small, the first term in (9) follows noncentral chi-square distribution with two degrees of freedom, in which the noncentrality parameter is $\lambda_{2,1} = S_{2,1}^2 / \sigma_{2,1}^2$, $S_{2,1} = \alpha \sqrt{2PL}$. The second term still follows central chi-square distribution with two degrees of freedom, with $\sigma_{2,2}^2 = \beta \sigma_{2,1}^2 = \beta \alpha LN_0 / 2$. Then the detection probability of the second stage is [2]:

$$P_{D2} = \int_{\gamma_2}^{+\infty} \frac{1}{2(1+\beta)\sigma_{2,1}^2} \exp\left(-\frac{Z_2}{2\beta\sigma_{2,1}^2}\right) \exp\left(-\frac{S_{2,1}^2}{2(1+\beta)\sigma_{2,1}^2}\right) \times Q\left(\frac{S_{2,1}^2}{\sigma_{2,1}^2} \sqrt{\frac{\beta}{(1+\beta)}}, \sqrt{\frac{2(1+\beta)Z_2}{\beta\sigma_{2,1}^2}}\right) dZ_2 \quad (20)$$

4. Results and Discussions

In this section, the proposed technique is tested for a GNSS receiver in an acquisition process of BOC(10,5) signal, sampling frequency $f_s = 4f_c$, correlation length is $4L = 4096$. Figure 2 shows the detection probability for BOC(10,5) versus SNR with a fixed false alarm probability $P_{fa} = 10^{-5}$ for $M_1 = \{128, 256, 512\}$ and $N_p = \{1, \lceil 0.05M_1 \rceil, \lceil 0.1M_1 \rceil\}$.

Figure 2. Overall Detection Probability of the Proposed Technique with versus SNR, M_1 and N_p

The detection probability is obtained from the 10^4 Monte Carlo simulation in the AWGN channel. It can be observed from Figure 2 that, for a fixed N_p , as the value of M_1 increases, the performance of the proposed technique gets better, because a greater compression ratio may bring a larger loss. Besides, when the value of M_1 is small, a greater N_p brings a better detection performance, but as M_1 increases, this conclusion does not hold water certainly. This is because for the fixed false alarm probability and M_1 , the threshold of the second stage measurement increases with the increase of N_p , when the value of M_1 is high, the influence of N_p on the threshold is not negligible.

Figure 3. Overall Detection Probability of the Proposed Technique, the DS Technique and Traditional Technique

In [10], the deterministic compressed GNSS acquisition technique has almost the same acquisition performance as the traditional technique with small η and $N_p(1 \ll N_p \ll M_1)$, a comparison among the proposed technique, the deterministic compressed acquisition technique and the traditional acquisition technique is shown in Figure 3. It can be seen that, when η is small and $1 \ll N_p \ll M_1$, the sensitivity of the proposed technique degrades about 2 dB compared with the traditional acquisition technique. This is because the sum operation in (9) introduces more noise. But the same as the DS technique, the proposed technique needs $M_1 + \eta M_2$ correlators, which is much less than the conventional parallel-correlator-based technique.

Figure 4. The ACF of BOC (10, 5) Signal, the Second Stage Measurement Test Criterion of the DS Technique and the Proposed Technique

Figure 4 shows the ACF R_b of BOC(10,5), the second stage measurement test criterion $Z_{2,DS}$ of the deterministic compressed acquisition technique in [10] and the second stage measurement test criterion $Z_{2,Proposed}$ of the proposed technique. All of the three curves are normalized. On the face of it, the test criterion curve of DS technique in [10] is triangular and has only one peak, but the ambiguous threat still exists, for $Z_{2,DS}$ can be considered as the absolute value of R_b . However for the proposed technique, the test criterion curve has only one positive peak, which is much narrower than the one in DS technique. This makes the proposed technique more reliable than the DS technique. In [2], the test criterion curve of GRASS also has one positive peak and the peak is narrower than the main peak of ACF of BOC (10,5), but Fig. 4 shows the opposite result, this is because the sampling frequency in this paper is lower than [2], which brings the difference.

5. Conclusion

In this paper, a two-stage measurement technique has been proposed to accomplish the unambiguous acquisition of BOC(m, n) signal. The detection performance and the test criterion in the second measurement of the proposed the technique have been analyzed and compared with the DS technique. It has been shown that, at the cost of some degradation of detection probability in acquisition the proposed technique can eliminate the ambiguity threat in the acquisition process by removing the undesired positive side peaks, which is much more reliable than the DS technique. It is therefore more reliable than the DS technique.

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