Research on Unambiguous Acquisition of BOC Modulated Navigation Signal

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Abstract. BOC (Binary-Offset-Carrier) modulation is widely used in the new generation of satellite navigation system. It has been used in GPS, Galileo and BeiDou systems. Compared with the traditional BPSK (Binary Phase Shift Keying) modulation, it has sharper correlation characteristics and stronger anti-multipath performance. The spectrum relocation caused by its splitting frequency can effectively solve the current frequency band congestion problem. But BOC modulation has multiple peak characteristics in the time domain, and the existence of sub-peak increases the difficulty of acquisition. Adding a pseudo-code correlation branch to the original BOC code correlation branch by using autocorrelation side-peak cancellation technique (ASPeCT) can effectively weaken the sub-peak of the correlation function and avoid wrong acquisition. This paper applies this ASPeCT acquisition algorithm to the parallel pseudo-random code FFT acquisition strategy to acquire the BeiDou-3 navigation signals. And the research object is the BOC (1,1) signal of the pilot component in BeiDou-3. Experimental results show that the method adopted in this paper can ensure the acquisition time and the acquisition accuracy reaches half a chip.

Keywords: BeiDou-3 · ASPeCT · FFT · Unambiguous acquisition

1 Introduction

China's BeiDou-3 satellite navigation system has released a modern civilian GNSS signal called B1C [1]. Compared to the satellite signal of BDS-2, the B1C signal of BDS-3 has been changed from the signal structure, encoding mode and navigation message structure. It introduces the pilot signal, secondary coding, BOC modulation, LDPC encoding and B - CNAV1 navigation message structure, etc. On the one hand, these changes improve signal performance, such as anti-multipath, signal acquisition and tracking accuracy, etc. But on the other hand, they also bring a series of problems, which put forward new requirements for signal acquisition technology of receivers, such as dealing with larger data streams, solving the problem of multi-peak autocorrelation function caused by secondary coding and BOC modulation.

The BOC (1,1) signal in the pilot component of BDS-3 is studied in this paper. The spread spectrum code used here is Weil code, whose code period is 10230 and lasts for

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10 ms. Such a long code period will make the amount of data to be processed very large during the acquisition process. The acquisition technique based on FFT is recognized to be computationally efficient. However, the price of the long FFT arithmetic module is very high, which limits the development of the actual receiver. When the sampling rate of 40 MHz is adopted in the modern navigation receiver, in order to complete the operation of a cycle, FFT operation must be performed on the data of more than 400,000 points, which cannot be realized by cheap FPGA resources selected by civilian receivers.

Secondly, although the peak value of the autocorrelation function of BOC modulated signal is more sharp than that of BPSK signal, it has multi-peak autocorrelation function, which can lead to the receiver to make mistakes in the acquisition procedure, resulting in a large error in the code phase estimation and difficulty getting into the tracking state. In the process of tracking phase, the tracking loop will be mistakenly locked to the side peak, which will lead to a large tracking error and cause the ambiguity of synchronous reception. Therefore, it is necessary to improve the search resolution as much as possible in order to avoid the false locking in the acquisition and tracking procedure.

Aiming at these two problems, this paper adopts the ASPeCT acquisition algorithm based on the parallel pseudo-random code FFT acquisition strategy. In the process of acquisition, firstly, partial accumulation of input data is used to reduce the rate of input data through average correlation technique [2, 3], and then ASPeCT algorithm [4] is used to realize the unambiguous acquisition of BOC (1,1) signal.

2 B1C Signal Structure

BOC modulation signal is obtained by multiplication of pseudo-random code and sub-carrier. It can be expressed as BOC (fs, fc), where fs is the ratio of rate between the carrier frequency and reference frequency, fc is the ratio of rate between pseudo random code and reference frequency. During modulation, the navigation data is firstly multiplied by pseudo random code, and then through subcarrier modulation, the signal is finally multiplied by the high frequency carrier signal, and the output is the satellite signal. The general expression of BOC modulation signal is:

$$s(t) = e^{-i\theta} \sum_{k} a_k \mu_{nT}(t - knT - t_0) c_T(t - t_0) \tag{1}$$

Where a_k is the navigation data, μ_{nT} is the satellite PRN code, c_T is the BOC sub-carrier, t_0 and θ is the time and phase delay.

We can obtain the autocorrelation function of BOC modulated signal by numerical method. Figure 1 shows its autocorrelation function compared with that of BPSK modulated signal. We can see it clearly that BOC modulation has multiple peak characteristics.

The carrier frequency of B1C signal which we studied in this paper is 1575.42 MHz, and it shares the frequency band with GPS L1 and Galileo E1, with a bandwidth of 32.736 MHz. A modern signal structure with orthogonal data and pilot frequency is adopted. The data component is generated by navigation message and ranging code through sub-carrier modulation, and sin-BOC (1, 1) modulation is adopted. The pilot component is generated by the ranging code via subcarrier modulation using QMBOC

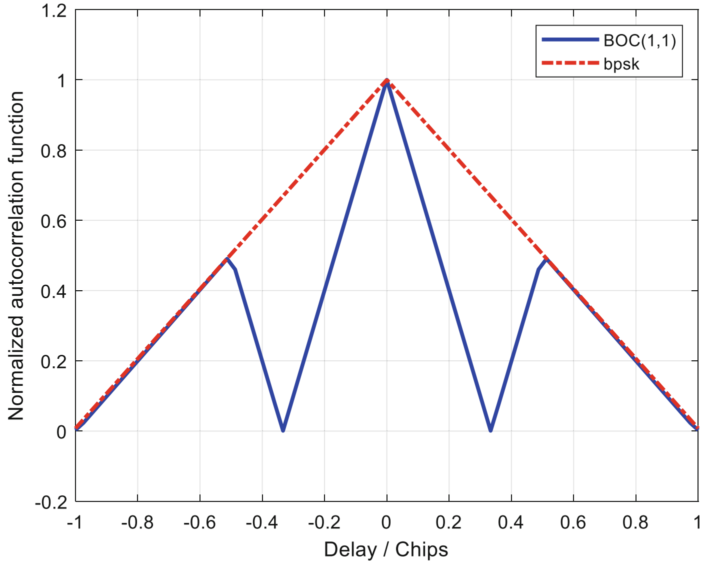

Fig. 1. BPSK and BOC (1,1) normalized autocorrelation function

(6,1,4/33) modulation. The power ratio between the data component and the pilot component is 1:3, and the designers place emphasis on the pilot component of signal power, which conforms to the design principle that the demodulation performance is sufficient, and the higher the ranging accuracy, the better, which is conducive to improving the overall performance of B1C signal.

The B1C signal can be written as a complex form:

$$S_{B1C}(t) = S_d(t) + jS_p(t) \tag{2}$$

Where, $S_d(t)$ is the data component of B1C signal, and $S_p(t)$ is the pilot component.

The mathematical expressions of data component and pilot component are:

$$S_d(t) = \frac{1}{2}D_d(t) \cdot C_d(t) \cdot sc_d(t) \tag{3}$$

$$S_p(t) = \frac{\sqrt{3}}{2}C_p(t) \cdot sc_p(t) \tag{4}$$

For the data component, due to the use of BOC (1,1) modulation, the sub-carrier is:

$$sc_d(t){=}sign(\sin(2\pi f_{sc1})t) \tag{5}$$

For the pilot component, QMBOC (6,1,4/33) modulation is adopted, and its sub-carrier is composed of BOC (1,1) and BOC (6,1), with mutually orthogonal phase and power ratio of 29:4:

$$sc_p(t){=}\sqrt{\frac{29}{33}}sign(\sin(2\pi f_{sc1})t){-}j\sqrt{\frac{4}{33}}sign(\sin(2\pi f_{sc2})t) \tag{6}$$

The complex expression of the whole B1C signal can be expressed as:

$$S_{B1C}(t) = \frac{1}{2} D_d(t) \cdot C_d(t) \cdot sign(\sin(2\pi f_{sc1})t) + \sqrt{\frac{1}{11}} C_p(t) \cdot sign(\sin(2\pi f_{sc2})t) + j\sqrt{\frac{29}{44}} C_p(t) \cdot sign(\sin(2\pi f_{sc1})t) \quad (7)$$

3 The Principle of ASPeCT Algorithm

For autocorrelation function characteristics of the signal BOC (1, 1), Julien proposed ASPeCT (Autocorrelation Side-Peak Cancellation Technique) algorithm1. And the principle of the algorithm is that BOC autocorrelation function is similar with BOC/PRN cross-correlation function in the side peak. Where BOC code means PRN code × square-wave subcarrier and that is the signal we received. To calculate the correlation of the sine-BOC (1,1) modulated spreading code with the PRN code only. And we write this consequence as $R_{BOC/PRN}(\tau)$, write the autocorrelation function of BOC signal as $R_{BOC/BOC}(\tau)$. The idea on which ASPeCT is based is to form a synthesized correlation function by subtracting $R^2_{BOC/PRN}(\tau)$ from $R^2_{BOC/BOC}(\tau)$ to remove the undesired side peaks. The mathematical expression of ASPeCT method is as follows:

$$R_{ASPeCT} = R^2_{BOC/BOC}(\tau) - \beta R^2_{BOC/PRN}(\tau) \quad (8)$$

Where β is a coefficient in the combination of the two squared correlation functions in order to eliminate any small remaining peak caused by a narrow front-end filter. This is successfully shown in Fig. 2.

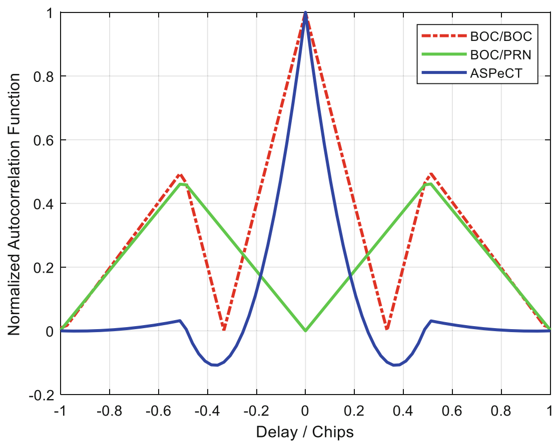

Fig. 2. Sine-BOC (1,1)/sine-BOC (1,1), sine-BOC (1,1)/PRN squared normalized correlation functions and ASPeCT modified correlation function

Figure 2 shows the output of the ASPeCT correlator of BOC (1,1) modulated signal. It can be seen that the side peak is completely reduced, and the new negative peak does not bring ambiguity. Figure 3 shows ASPeCT discriminator output for a sine-BOC (1,1) signal. It also shows the traditional BOC discriminator output using the same early-late discriminator. We can see the error locking point disappears, and the phase discriminator gain increases slightly, and the noise performance improves.

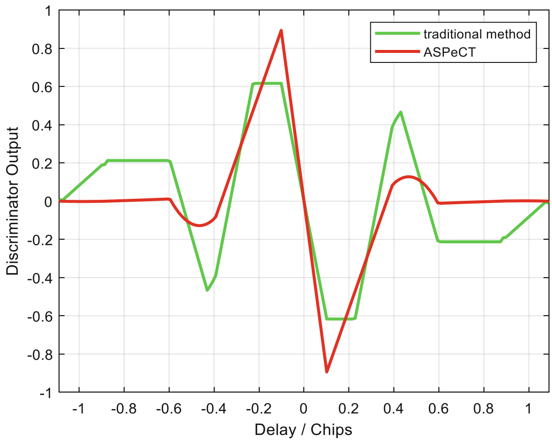

Fig. 3. Discriminator output

Figure 4 shows the multipath-induced error envelope for traditional sine-BOC (1,1) tracking, as well as for ASPeCT, in which the spacing of early and late correlators is 0.1 chip. ASPeCT algorithm reduces the envelope amplitude of multipath error and minimizes the maximum delay affected by multipath signals, thus improving the anti-multipath performance. The ASPeCT algorithm not only removes the ambiguity of BOC (1,1) signals, but also further improves the acquisition accuracy and anti-multipath performance.

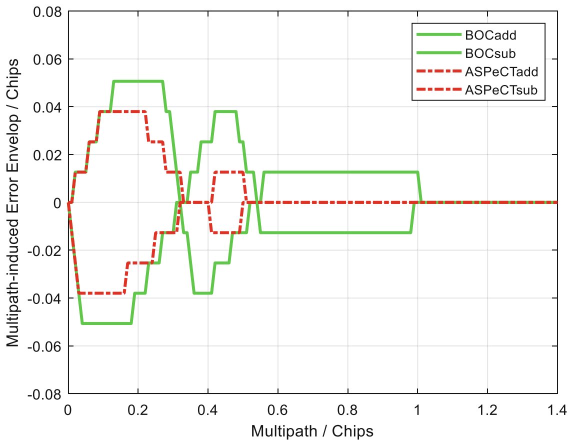

Fig. 4. Multipath-induced error envelope

4 Parallel Code Phase Search Acquisition Algorithm Based on FFT

ASPeCT algorithm has been shown to be reliably unambiguous for BOC (1,1) signal acquisition. Therefore, next, ASPeCT algorithm is applied to the traditional acquisition algorithm to realize the unambiguous acquisition of BOC signal. Figure 5 is the flow chart of the ASPeCT acquisition algorithm based on two-dimensional parallel and fast search [5].

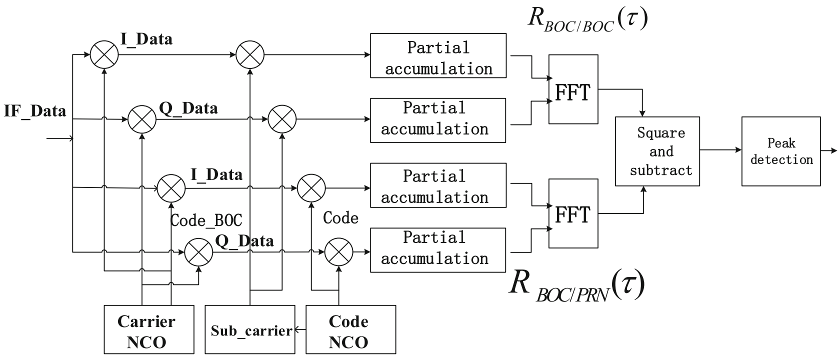

Fig. 5. The flow chart of the ASPeCT acquisition algorithm based on two-dimensional parallel and fast search

Firstly, the BOC signal received was multiplied with the sines and cosines of the local carrier to generate the zero-IF signals, written as I_Data and Q_Data. And then they were correlated with the locally generated pseudo-code sequence, Code without sub-carrier and Code_BOC modulated by the sub-carrier. Since the sampling frequency in the simulation is 40 MHz and the number of sampling points in a pseudo-code period is about 400,000, the time and resources required to directly carry out FFT will be very large, so before carrying out FFT, we can conduct 40 times reduction sampling and partial accumulation to reduce the data volume. After FFT, square the transformation results of the two relevant branches and subtract $R^2_{BOC/PRN}(\tau)$ from $R^2_{BOC/BOC}(\tau)$ to generate the detection value. If there is a peak value, the acquisition is successful. If there is no peak value, change the local code phase and repeat the above steps until the acquisition is successful. In the FPGA design, we can add more correlator resources to search multiple code phases at one time in the code phase dimension.

In the operation of FFT, frequency resolution is as follows:

$$\Delta f = \frac{1}{N\_FFT * X * T_S} \tag{9}$$

Where, N_FFT is the points of FFT, X is the length of partial accumulated data, and T_S is the time length of a pseudo-code. In this matlab simulation, the expected doppler frequency search range is −50–50 kHz. According to BeiDou Navigation Satellite System Signal In Space Interface Control Document [1], symbol rate Rb of BeiDou-3 navigation signal is 100 sps, pseudo-code period N is 10230, pseudo-code rate Rc is $1.023 * 10^6$

Mbps, pseudo-code period Tc equals 1/Rc, so the range of each FFT point which can be searched is

$$\frac{1}{N \cdot T_C} = R_b = 100 \text{ Hz} \tag{10}$$

Therefore, the number of FFT points, N_FFT, is 100 k/100=1000. To facilitate FFT operation, take 1024 points. Then, the number of partial accumulators, X=N/N_FFT, and take X=10.

The three-dimensional acquisition of BOC (1,1) using ASPeCT algorithm is shown in the figures. Figure 6 shows the acquisition result of the traditional approach when

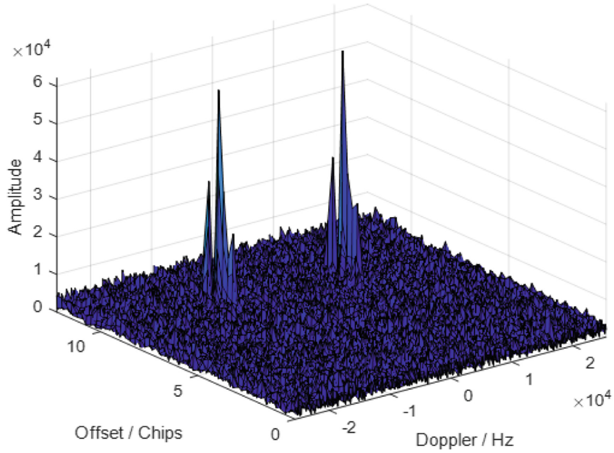

Fig. 6. The acquisition result of the traditional algorithm

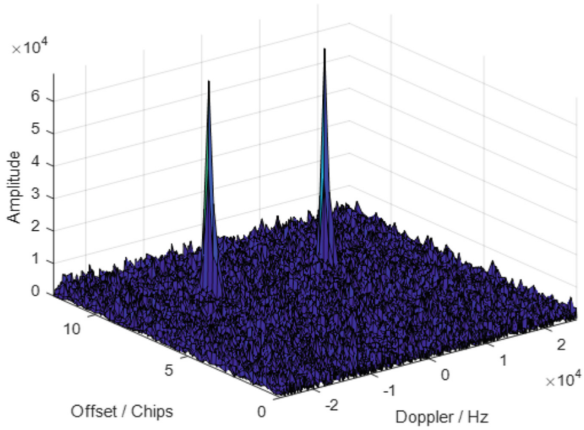

Fig. 7. The acquisition result of the ASPeCT algorithm

BOC (1,1) code phase offset is 8.5 chips, doppler frequency shift is 10 kHz, and signal-to-noise ratio is –21 dB. Figure 7 shows the acquisition result of the ASPeCT algorithm under the same conditions.

It can be seen from the figure that the ASPeCT algorithm can well eliminate the side peak, and ensure that the chip search accuracy reaches half a chip and the frequency resolution reaches 100 Hz.

5 Conclusion

In order to eliminate the side peak of BOC modulation signal, avoid the wrong acquisition, the ASPeCT algorithm, on the basis of the original BOC code related branch, adds a pseudo code correlation branch. Implementation scheme is more complex. Each search only one unit can't satisfy the BOC signal dynamic acquisition. This paper presents the ASPeCT acquisition algorithm based on the parallel pseudo-random code FFT acquisition strategy to acquire the BeiDou-3 navigation signals. In the code phase dimension, multiple code phases are searched by adding more correlators. In the doppler frequency dimension, all frequency units are searched by Fourier transform at one time, which significantly reduces the acquisition time on the premise of ensuring accuracy. Theoretical analysis and simulation verify the correctness and effectiveness of this scheme.

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