Research on Beidou B1C Signal Joint Tracking Algorithm Based on Pseudo Correlation Function

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Abstract. The Beidou B1C signal is a new type of navigation signal used by the Beidou III system. Compared with traditional satellite navigation signals, this navigation signal has two significant characteristics: one is the use of BOC(Binary-Offset-Carrier) modulation, and the other is the separation of the data channel and the pilot channel. BOC modulation has multi-peak characteristics, which leads to ambiguity in tracking, while the PCF(Pseudo-Correlation-Function) algorithm can eliminate related secondary peaks of the BOC signal; the separation of the data channel and the pilot channel results in the dispersion of signal energy. Therefore, based on the PCF algorithm, this paper proposes a linear joint tracking algorithm suitable for B1C signals from the perspective of engineering applications. Finally, it is verified that the tracking accuracy of the proposed algorithm is better than the single-component PCF tracking algorithm.

1. Introduction
Satellite navigation is widely used in all areas of life, and it can provide positioning, navigation and time service[1]. Due to the increase in the number of satellites and the shortage of frequency band resources, it is easy to cause mutual interference among satellite signals. To avoid this, Jhon W. Betz proposed BOC modulation[2]. The biggest feature of BOC modulation is that the main lobe of the signal power spectrum is split into two symmetrical parts, and the distance between the two split lobes can be adjusted according to parameters. This can not only make good use of space frequency band resources, but also avoid mutual interference of satellite signals. In order to pursue higher tracking accuracy, various countries have studied MBOC modulation on the basis of BOC modulation. MBOC modulated signals are a new signal modulation method obtained by combining multiple BOC signals[3]. The system also announced the B1C signal using QMBOC modulation on December 27, 2017[4]. However, the autocorrelation functions of BOC and MBOC signals have multi-peak characteristics, which leads to ambiguity in tracking[5]. In order to eliminate the ambiguity of tracking, Julien proposed a code tracking loop scheme based on ASPeCT(Autocorrelation side-peak cancellation technique)[6], it can attenuate related subpeaks but cannot completely eliminate them. Zheng Yao of Tsinghua University proposed a correlation peak elimination method based on a pseudo correlation function[7], it can completely eliminate the associated side peaks. So I chose the PCF algorithm to eliminate tracking ambiguity, but this method only tracks a single signal component, which will cause the loss of useful signal energy, resulting in reduced tracking accuracy. Therefore,
based on this, this paper proposes a tracking method combining data components and pilot components, which not only eliminates the ambiguity of B1C signal tracking, but also improves the tracking accuracy of B1C signals.

2. B1C signal characteristics

The Beidou B1C signal is composed of a data component and a pilot component, and the two are orthogonal. The data component is modulated by BOC, and the pilot component is modulated by QMBOC(6,1,4/33). The power ratio of the two is 1: 3. Its mathematical expression is as follows:

\[ S_{B1C\_data}(t) = \frac{1}{2} D_{B1C\_data}(t) \cdot C_{B1C\_data}(t) \cdot sc_{B1C\_data}(t) \]  
\[ S_{B1C\_pilot}(t) = \frac{\sqrt{3}}{2} C_{B1C\_pilot}(t) \cdot sc_{B1C\_pilot}(t) \]  

Where \( D_{B1C\_data} \) is the navigation message, \( C_{B1C\_data} \) is the spreading code for the data component, \( sc_{B1C\_data} \) is the subcarrier signal for the data component, \( C_{B1C\_pilot} \) is the spreading code for the pilot component, and \( sc_{B1C\_pilot} \) is the subcarrier signal for the pilot component.

The pilot component of the B1C signal consists of a combination of BOC(1,1) and BOC(6,1) signals that are orthogonal to each other. The power ratio of the two is 29: 4. Its expression is:

\[ S_{QMBOC}(t) = \frac{29}{33} S_{BOC(1,1)}(t) - j \frac{4}{33} S_{BOC(6,1)}(t) \]  

The power of the B1C signal is:

\[ G_{B1C} = \frac{1}{4} G_{data}(f) + \frac{3}{4} G_{pilot}(f) = \frac{10}{11} G_{BOC(1,1)}(f) + \frac{1}{11} G_{BOC(6,1)}(f) \]  

The autocorrelation function of the data component and pilot component of the B1C signal is:

\[ R_{BOC}(\tau) = R_{BOC(1,1)}(\tau) \]  

\[ R_{QMBOC}(\tau) = E\{ S_{QMBOC} S_{QMBOC}^* \} = \frac{29}{33} R_{BOC(1,1)}(\tau) + \frac{4}{33} R_{BOC(6,1)}(\tau) \]  

The power spectrum and autocorrelation function of the B1C signal are shown in Figure 1.

Fig.1 Power spectrum and autocorrelation function of B1C signal

The power spectrum of the BOC modulation signal obtained from the left figure has a multi-peak phenomenon, because the modulated subcarrier signal is a sin signal, and the larger the modulation coefficient, the farther away from the center frequency. And we can see the superposition relationship between the power spectrum of B1C signal and the power spectrum of BOC(1,1) and BOC(6,1). From the figure on the right, it can be seen that compared to traditional PSK modulation, the autocorrelation functions of BOC modulation signals have multi-peak characteristics, and the larger the modulation...
coefficient, the more correlated sub-peaks, but the narrower the main correlation peak, the better the tracking accuracy high. On the other hand, the QMBOC modulation signal has a narrower main peak relative to the BOC(1,1) modulation signal. Compared to the BOC(6,1) modulation signal, the amplitude and number of the related subpeaks are greatly reduced.

3. PCF algorithm and proposed method

3.1. PCF algorithm
The PCF tracking algorithm can well eliminate the relevant secondary peaks of the autocorrelation function of BOC-type signals, thereby eliminating the ambiguity of signal tracking[7]. Its main principle is to use two sets of BOC-like signals that are locally mirrored with each other, respectively. Correlation operation is performed with the BOC signal, and then the correlation results are linearly combined to obtain a pseudo-autocorrelation function with only relevant main peaks and no correlated side peaks, and the signal can be tracked without ambiguity. The pseudo-autocorrelation function of the BOC modulated signal is:

\[ R(\tau) = |R_{s1} (\tau)| + |R_{s2} (\tau)| - |R_{s1} (\tau) + R_{s2} (\tau)| \]  

Where, \( R_{s1} (\tau) \) and \( R_{s2} (\tau) \) are cross-correlation functions of local BOC-like signal and BOC(1,1) signal.

Using MATLAB to verify the PCF algorithm can eliminate the secondary peaks of the BOC signal correlation function. Use MATLAB to generate BOC(1,1) signals, and at the same time, use symbols \( d^{(1)} = [\sqrt{2}, 0] \) and \( d^{(2)} = [0, \sqrt{2}] \) modulate pseudo code sequences to generate local BOC-like signals, and then perform correlation operations with the locally generated BOC(1,1) signals. Finally, a linear combination is obtained to obtain a pseudo-correlation function. The simulation diagram is shown in Figure 2.

![Fig.2 autocorrelation function and pseudo-correlation function](image)

It can be seen from the figure that the correlation function waveform of the BOC signal and the local BOC-like signal are the same, and are symmetrical about the center of the origin. Compared with the BOC(1,1) autocorrelation function, the pseudo-correlation function has no associated side peaks, which completely eliminates the ambiguity of tracking.

3.2. Proposed method
Since the B1C signal is composed of a data component and a pilot component, and the modulation pseudocodes of the two are orthogonal, if PCF is used for tracking, only a single component of the signal energy is used. If the pilot component with a larger tracking energy is used, it will cause 25% signal energy loss. The signal energy affects the signal tracking accuracy. Therefore, in order to make full use of the signal energy and improve the signal tracking accuracy, a data component tracking
branch is added on the basis of the original pilot component tracking. Linearly combine the results of the pseudo-code phase detector to make full use of the signal energy; meanwhile, the BOC(1,1) signal occupies most of the energy, while the BOC(6,1) signal occupies a small amount of energy, and the tracking of the BOC(6,1) signal requires a small correlation interval. This requires a higher sampling frequency of the receiver and is not easy to implement. Therefore, from the perspective of engineering applications, the viewpoint of using the BOC(1,1) signal as the main tracking signal is proposed, and the data branch and the pilot branch are linearly combined. Therefore, the pseudo-code linear joint tracking structure based on the PCF algorithm is shown in Figure 3.

As can be seen from the figure above, the proposed method tracks the data component and pilot component of the digital IF signal separately. The two-channel discriminator results are linearly combined. After passing through the loop filter, the control code NCO generates the corresponding phase. Data component spread signal and pilot component spread signal. Since the tracked signals are BOC(1,1) signals, set Symbol 1 and Symbol 2 to

\[
\begin{align*}
\text{Symbol 1} & = 20d, \\
\text{Symbol 2} & = 02d.
\end{align*}
\]

The Symbols of the data component and the pilot component are the same. The tracking process of the data channel and the pilot channel is the same except that the pseudo code sequence is different. The following is an analysis of the pilot channel. The pseudo-correlation function generated by the pilot component early and late branches is:

\[
R_p^e = \sqrt{(I_{p1}^e)^2 + (Q_{p1}^e)^2} + \sqrt{(I_{p2}^e)^2 + (Q_{p2}^e)^2} - \sqrt{(I_{p1}^e + I_{p2}^e)^2 + (Q_{p1}^e + Q_{p2}^e)^2}
\]

\[
R_p^l = \sqrt{(I_{p1}^l)^2 + (Q_{p1}^l)^2} + \sqrt{(I_{p2}^l)^2 + (Q_{p2}^l)^2} - \sqrt{(I_{p1}^l + I_{p2}^l)^2 + (Q_{p1}^l + Q_{p2}^l)^2}
\]

The phase difference between the pilot code of the pilot channel can be obtained by sending the early branch and the late branch as a correlation function into the pseudo code discriminator. The pseudo code discriminator uses the early and late power reduction method, and the pilot channel pseudo code phase error expression is:
Similarly, the pseudo-code phase deviation of the data channel can be obtained. The combined weighting coefficient of the data component and the pilot component phase detector output refers to the power ratio of the data component and the pilot component. Because only the BOC(1,1) signal is used for tracking, the power ratio of the data component and the pilot component is 11:29. The following pseudo-code loop phase estimation error is:

$$
\Delta \tau = \frac{11}{40} \Delta \tau_d + \frac{29}{40} \Delta \tau_p
$$

(11)

Where, $\Delta \tau_d$ is the data channel pseudo code tracking error, $\Delta \tau_p$ is the pilot channel pseudo code tracking error, and $\Delta \tau$ is the pseudo code discriminator joint tracking error.

4. Simulation and analysis

The theoretical analysis of the dual channel joint tracking of B1C signals based on the PCF algorithm was performed above. In order to compare the performance of single component tracking and dual channel joint tracking, this paper performs Matlab simulation on single pilot channel tracking and dual channel joint tracking of B1C signals. The parameters set by the simulation are shown in Table 1.

Table 1. Simulation parameters of the algorithm.

| Parameter                        | Value     |
|----------------------------------|-----------|
| Simulation time                  | 2.5s      |
| IF frequency                     | 8MHz      |
| Sampling frequency               | 32.736MHz |
| Coherent integration time        | 10ms      |
| CNR                              | 40dB/Hz   |
| Code ring bandwidth              | 2.6Hz     |
| Early / Late branch related interval | 0.125chip |

The simulated pseudo-code tracking error curve is shown in Figure 4.

![Figure 4: Code tracking error curve comparison](image)

From the tracking error curve, it can be seen that stable tracking of the signal can be achieved at about 500ms. The standard deviation of the tracking code tracking error is usually used to measure the
accuracy of the code tracking accuracy. By calculation, it can be obtained that the CNR is 40 dBHz. The single pilot channel tracking accuracy is 1.3812m, the dual channel tracking accuracy is 0.8949m, and the tracking accuracy is improved by 0.4863m.

After verifying the feasibility of the algorithm, adjust CNR in the channel, and the change trend of the code tracking error with different CNR is shown in Figure 5.

It can be obtained from Figure 5 that as the CNR increases, the pseudo-code tracking of the signal becomes more accurate, and under low CNR, the dual-channel tracking error is more significantly reduced than the single-channel error.

5. Conclusion
This paper proposes a pseudo-code tracking structure for B1C signals based on the PCF algorithm, which uses a combination of pilot components and data components to implement signal tracking. From the simulation results, dual-channel tracking has less error at low CNR than single-channel tracking, and has better application value.

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