# Satellite Navigation Software Receiver Design

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**Abstract.** The establishment of the Global Navigation Satellite System can provide users with precise navigation information, including speed, three-dimensional position and precise time. In this paper, the signal structure of Beidou B1I is introduced firstly. Then, based on the known rough carrier Doppler frequency shift and pseudo-code phase, this paper analyzes the different forms of carrier loops, including FLL, PLL and FLL+PLL carrier loops. The advantages and disadvantages of their performance are compared. Finally, the simulation and data demodulation results are given.

**Keywords:** Satellite navigation software receiver · BDS · Tracking

## 1 Introduction

The satellite navigation uses satellites to broadcast radio signals, and users on the surface of the earth can obtain navigation and positioning information after processing the signals. Satellite navigation has the advantages of not being restricted by distance, little affected by weather conditions, and high accuracy of navigation and positioning. At present, there are multiple satellite navigation systems in the world, which can be divided into global systems and regional systems. The global systems include the United States' Global Positioning System (GPS), Russia's Global Navigation and Positioning System (GLONASS), the European Union's Galileo System (Galileo), China's Beidou System (BDS). The regional systems include Japan's Quasi-Zenith Satellite System (QZSS), and The IRNSS system in India [1].

With the construction of global satellite navigation systems, such as GPS, GLONASS, Galileo, and BDS, the number of satellites will increase significantly, along with the emergence of new modulation methods and signals at various frequencies, which will greatly promote the development of satellite navigation and the upgrading of navigation receiver equipment.

The research of software receiver technology has been relatively mature abroad, among which the United States first started the research of GPS receiver software. In 1995, Dr. Clifford Kelley of the United States designed the first GPS software receiver and made the project public [2]. The U.S. Data Fusion Corporation developed a GPS single - frequency L1 intermediate frequency software receiver and signal source tool based on MATLAB/C in 2001 [2]; Standford University in the United States and Lulea University of Science and Technology in Sweden have developed a GPS L1 four-channel real-time software receiver. The receiver is all realized by software programming from the

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acquisition of IF signals to the localization solution, and then they continued to cooperate and developed GPS/Galileo multi-frequency compatible software receiver [3]. In 2004, the Ledvina team at Cornell University designed the first dual-frequency GPS receiver based on the Linux system, which satisfies the real-time positioning of signals in the L1 and L2C frequency bands [2]; The GPS Center of the University of Alborg in Denmark developed GPS software based on MATLAB accepted the test prototype, and published GPS and Galileo software receiver development plans and monographs in 2005 and 2007 [4]. ZAHIDUL et al. of Finland designed the software receiver of Beidou B1 frequency point in 2014 with positioning accuracy within ±5 m; the U.S. university of Texas proposed a graphical implementation method for GPS receiver, including two modes of acquisition and tracking [2].

In 1998, the team of Professor Zhang Qishan designed the first GPS L1 single frequency point software receiver in China in 1998 on the platform of PC machine [5]. In 2004, Dr. Lu Yu, a GPS senior software engineer, wrote a complete set of GPS receiver programs in C language, and released it as an open source [2]. In 2012, Zhao Pu of Fudan University developed a software receiver of Beidou B2 frequency based on FPGA + host computer. By processing the signal with baseband digital signal, it can achieve very good accuracy, verifying the practicality of Beidou platform. ZHANG et al. developed the first open source dual-frequency software receiver in china in 2014, which can be compatible with GPS signals of L1 and L2C frequency points simultaneously [5]. In 2015, YIN et al. of Beijing Institute of Microelectronics Technology proposed a dual-mode vector software receiver compatible with four frequency points, It can support GPS L1, L2 signals and Beidou B1, B3 signals at the same time, the positioning results It shows that the performance of vector tracking technology is better than that of ordinary tracking loop [6].

This article will study from BDS system. First introduce the basic overview, including the composition and structure of their satellite signals. The core of this article is the software implementation of digital baseband signal processing such as tracking. The chapters of the paper are organized as follows:

(1) BDS B1I signals. The Beidou Satellite Navigation System is introduced firstly, then the structure of BDS B1 signals are introduced in detail, which includes three levels: data code, ranging code and carrier wave.

(2) Research on signal tracking algorithm. This chapter first briefly introduces the basic principles of tracking, and then analyzes the carrier loop and code loop used in the tracking process. Three implementation forms of the carrier tracking loop are analyzed. Finally, the tracking and data demodulation are realized, and the simulation results are given.

## 2 BDS B1I Signal

### 2.1 Introduction to the BDS

The Beidou Satellite Navigation System (BDS) is a self-developed global satellite navigation system with independent intellectual property rights. BDS has now developed to the third generation, and the Beidou-3 system officially provides global services in September 2019.

## 2.2 Signal Structure

The Beidou-2 satellite signal consists of navigation messages, ranging codes and carrier waves. In this paper, B1I signal of BDS-2 is simulated, and the B1 signal structure is shown in Fig. 1.

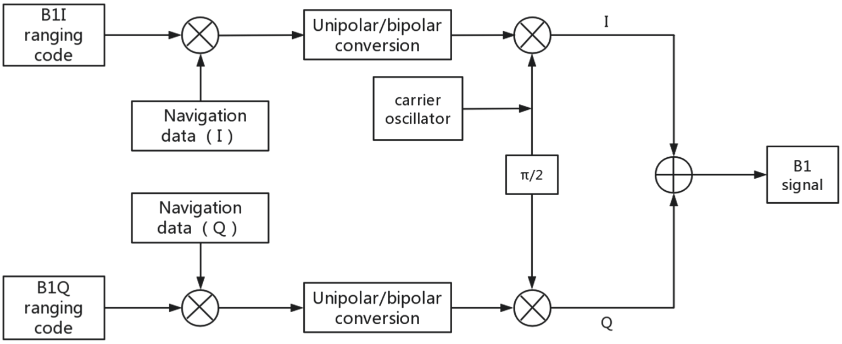

**Fig. 1.** B1 signal structure of Beidou-2

The expression of B1 signal is as follows.

$$S^j(t) = A_I C_I^j(t) D_I^j(t)\cos(\omega_0 t + \phi_I^j) + A_Q C_Q^j(t) D_Q^j(t)\sin(\omega_0 t + \phi_Q^j) \quad (1)$$

In this formula, two orthogonal I and Q branches form the signal at frequency B1. The I branch is open for use, and the Q branch is not open to the outside. $C_I^j(t)$ and $C_Q^j(t)$ are the ranging codes of the in-phase and orthogonal branches of the $j$ satellite respectively. $A_I$ and $A_Q$ are the amplitudes of the I and Q ranging codes. $D_I^j(t)$ and $D_Q^j(t)$ are the data codes of the I and Q channels of the $j$ satellite. $\omega_0$ is the angular frequency of the carrier of the signal. $\phi_I^j$ and $\phi_Q^j$ are the initial phases of the carrier of the I and Q branches of the $j$ satellite respectively.

### 2.2.1 Carrier

The Beidou system currently has three carrier frequencies. B1 frequency: 1559.052–1591.788 MHz; B2 frequency: 1166.22–1217.37 MHz; B3 frequency: 1250.618–1286.432 MHz. Based on the above three frequencies, selecting a dual-frequency signal can make use of the difference in the ionospheric delay between the two carrier frequencies of the signal, thereby reducing and eliminating the ionospheric delay.

The use of three-frequency signals has faster carrier convergence speed, smaller ionospheric delay errors, and more accurate positioning effects than dual-frequency signals [6].

### 2.2.2 The Structure of Ranging Code

The Beidou B1 signal modulates different ranging codes on the I and Q branches. The I branch is modulated $C_{B1I}$ Code, P code is modulated in the Q branch. $C_{B1I}$ code is similar to C/A code, both of them can be generated by linear feedback shift registers. $C_{B1I}$ code also belongs to a Gold code, which is 2046 chips in length and is repeated one period per millisecond. It can transmit 2.046 M symbols per second. The satellite can generate $C_{B1I}$ code by a linear combination of two 11-stage feedback shift registers of its internal circuit, and the structure of its generator is shown in Fig. 2.

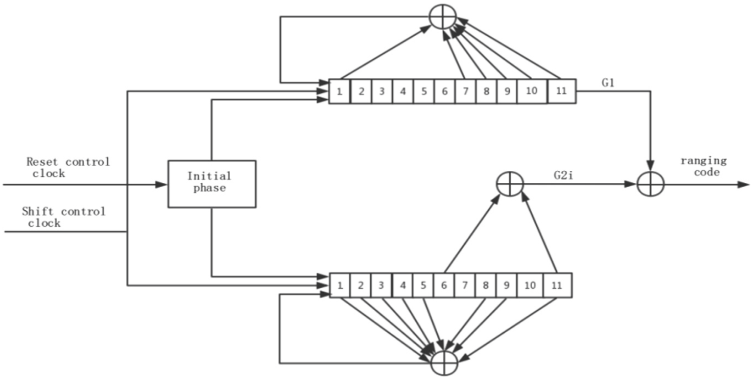

**Fig. 2.** $C_{B1I}$ code generator structure

The $C_{B1I}$ code can be generated by truncating one chip from the balanced Gold code obtained after modulo 2 sum of two linear sequences $G_1$ and $G_{2i}$ [7]. The characteristic polynomials are as follows:

$$\begin{aligned} G_1(x) &= 1+x+x^7+x^8+x^9+x^{10}+x^{11} \\ G_2(x) &= 1+x+x^2+x^3+x^4+x^5+x^8+x^9+x^{11} \end{aligned} \tag{2}$$

The initial phases of the sequence $G_1$ and $G_2$ are both 01010101010. Similar to the C/A code, two different register units are selected in the generator, corresponding to the $C_{B1I}$ code of different satellites. The following figure shows the phase selector distribution of $C_{B1I}$ codes corresponding to different satellite PRN numbers (Table 1):

**Table 1.** PRN number and corresponding $G_{2i}$ select

| PRN | Satellite type | $G_{2i}$ |
|---|---|---|
| 1 | GEO | $1 \oplus 3$ |
| 2 | GEO | $1 \oplus 4$ |
| 3 | GEO | $1 \oplus 5$ |
| 4 | GEO | $1 \oplus 6$ |
| 5 | GEO | $1 \oplus 8$ |
| 6 | MEO/IGSO | $1 \oplus 9$ |
| 7 | MEO/IGSO | $1 \oplus 10$ |
| 8 | MEO/IGSO | $1 \oplus 11$ |
| … | … | … |
| … | … | … |
| 33 | MEO/IGSO | $8 \oplus 10$ |
| 34 | MEO/IGSO | $8 \oplus 11$ |
| 35 | MEO/IGSO | $9 \oplus 10$ |
| 36 | MEO/IGSO | $9 \oplus 11$ |
| 37 | MEO/IGSO | $10 \oplus 11$ |

### 2.2.3 Data Code

The B1 signal on the MEO and IGSO satellites is modulated with navigation messages D1 with a rate of 50 bps, and also has a secondary encoding, which is modulated by a 20-bit NH code with a rate of 1 kbps [3]. The signal transmitted on the GEO satellite does not use secondary coding, but its navigation messages is different from D1, and the transmission rate of the navigation message D2 is 500 bps.

Secondary encoding refers to the modulation of Neuman-Hoffman codes (NH codes) on D1 navigation messages. NH code transmits 1k bits per second, and repeats for one period every 20 ms. In one period, it contains 20 ranging code period (ranging code period is 1 ms). Each chip in the NH code has the same width as the ranging code period. NH code has 20 bits in total, its sequence is 00000100110101001110.

# 3 Research on Signal Tracking Algorithm

## 3.1 The Fundamentals of Signal Tracking

When the acquisition is completed, the value of the carrier Doppler frequency shift and code phase of a certain satellite signal can be obtained. But these values are rough, so the carrier and ranging code cannot be completely stripped. Therefore, after the acquisition, it is necessary to use the loop to keep the tracking of the signal, and get more accurate carrier Doppler frequency shift and code phase values. For Doppler frequency shift, a carrier tracking loop is usually used to keep tracking, and the carrier signal copied by carrier generator is adjusted according to the Doppler shift until the copied carrier is as same as the received signal carrier. After mixing, the carrier can be completely stripped and the Baseband signal can be obtained. For the code phase, the code tracking loop is usually used to track, and the phase of the copied ranging code is adjusted according to the obtained code phase value. When the copied code is aligned with the code phase of the received signal, the ranging code can be stripped completely after multiplying. At this moment, only the navigation messages are left in the signal, and the information required for navigation can be obtained.

## 3.2 Carrier Tracking Loop

The carrier tracking loop tracks the Doppler shift of the received signal, and adjusts the copied carrier signal by the carrier generator according to the Doppler shift, until the copied carrier is as same as the received signal carrier. The carrier tracking loop usually has two forms: phase locking loop PLL and frequency locking loop FLL. This paper will introduce PLL and FLL respectively, then discuss a compound carrier loop with FLL to assist PLL.

### 3.2.1 Phase Lock Loop (PLL)

In the tracking process, there is a difference between the copied carrier and the carrier of the received signal. If the phase difference is used as the feedback amount to adjust the phase of the copied carrier, this loop is called phase locked loop (PLL) [7]. In the satellite signal, the navigation data will flip, causing the carrier to produce a 180° phase flip. Therefore, the phase-locked loop is generally a Costas loop, which is not sensitive to phase reversal. The structure is shown in Fig. 3.

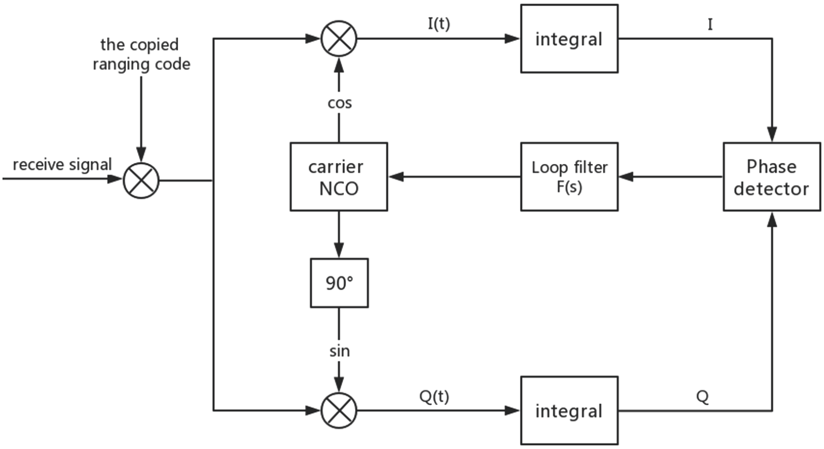

**Fig. 3.** The structure of Costas loop

In the Costas loop, the carrier generator is used to generate the copied sine-cosine carriers with frequency close to the intermediate frequency. Then the ranging code generator is used to generate the copied ranging codes with certain code phases of the satellite. (Here it is assumed that the copied ranging code is consistent with the phase of the received signal ranging code). The received signal is multiplied by the copied ranging code to realize the ranging code stripped. Then the obtained signal is multiplied and mixed with the sine and cosine carriers respectively, where the sine branch is the in-phase branch (I branch), and the cosine branch is the orthogonal branch (Q branch). Because the received signal contains noise, and the noise power is generally greater than the useful signal power. Therefore, coherent integral filtering with time T is needed to filter out the high frequency components and improve the SNR at the same time. After that, the integral results are sent into the phase discriminator. Different phase discriminator algorithms can be used to obtain the phase difference between the copied carrier and the received signal carrier. Then the phase difference is taken as the feedback quantity to adjust the phase of the copied carrier [8]. Common phase discriminator algorithms are shown in Table 2.

**Table 2.** Common phase discriminator algorithms

| Phase discriminator algorithms | Output phase difference | Characteristic |
|---|---|---|
| $I(t) \times Q(t)$ | $\sin(2\varphi(t))$ | It still has good performance when the signal-to-noise ratio is low, but its phase discrimination result is proportional to the square of the signal amplitude, and the amount of calculation is moderate |
| $\arctan(\frac{Q(t)}{I(t)})$ | $\varphi(t)$ | The work of the phase detector remains linear, and the phase detection result has nothing to do with the signal amplitude, and the amount of calculation is the largest |
| $\frac{Q(t)}{I(t)}$ | $\tan(\varphi(t))$ | The phase detection result has nothing to do with the amplitude, and the calculation amount is relatively large |
| $Q(t) \times \mathrm{sgn}(I(t))$ | $\sin(\varphi(t))$ | The phase discrimination result is proportional to $\sin(\varphi(t))$ and also related to the signal amplitude, so the amount of calculation is minimal |

### 3.2.2 Frequency Lock Loop (FLL)

In the tracking process, there is a difference between the copied carrier and the carrier of the received signal. If the frequency difference is used as the feedback amount to adjust the frequency of the copied carrier, this loop is called frequency locked loop (FLL) [7]. The frequency locked loop is similar to the phase locked loop. The difference between them is the discriminator. This section focuses on the discriminators used in FLL.

Before introducing a variety of frequency discriminators, first define a few parameters.

$$\begin{aligned} P_{dot} &= I_P(n-1)I_P(n) + Q_P(n-1)Q_P(n) \\ P_{cross} &= I_P(n-1)Q_P(n) - Q_P(n-1)I_P(n) \end{aligned} \tag{3}$$

In the formula, $P_{dot}$ is the dot product. $P_{cross}$ is the cross product. $I_P(n)$ and $Q_P(n)$ are the I/Q coherent integration results obtained from epoch n. There are three main frequency identification methods used in FLL.

① Four-quadrant arctangent frequency discriminator

$$\omega_e(n) = \frac{\arctan 2(P_{cross}, P_{dot})}{t(n) - t(n-1)} \tag{4}$$

In the formula, $\omega_e(n)$ is the angular frequency error. $t(n) - t(n-1)$ is the time T of coherent integration. This method has a large amount of calculation, but it is the most accurate frequency discrimination method. The frequency discrimination result has nothing to do with the amplitude of the signal. Therefore, it is often selected in practice. The frequency pulling range is $\left[-\frac{1}{2T}, \frac{1}{2T}\right]$.

② Cross product discriminator

$$\omega_e(n) = \frac{P_{cross}}{t(n) - t(n-1)} \tag{5}$$

This method has a small amount of calculation, but the frequency discrimination result is proportional to the product of the signal amplitude, and its frequency pulling range is $\left[-\frac{1}{2T}, \frac{1}{2T}\right]$. However, this method is sensitive to the jump of the navigation messages, so some processing is required in application.

③ Symbol Dot Cross Product Discriminator

$$\omega_e(n) = \frac{P_{cross} \cdot sign(P_{dot})}{t(n) - t(n-1)} \tag{6}$$

This method has a small amount of calculation, and the frequency discrimination result is proportional to the square of the signal amplitude. The frequency pulling range is $\left[-\frac{1}{4T}, \frac{1}{4T}\right]$. Because $sign(P_{dot})$ can detect the phase reversal caused by the data bit jump, this method is not sensitive to the data bit jump.

### 3.2.3 Comparison and Combination of FLL and PLL

Both phase-locked loop and frequency-locked loop are often used in the tracking process. Their structures are similar, but the difference is the discriminator, which results in differences in noise and dynamic performance [9].

① The noise bandwidth of the phase-locked loop is narrow. The phase-locked loop can generate a signal with the same frequency and stable phase error. The signal can be closely tracked and the output phase value is accurate. Although the phase-locked loop has many advantages, its disadvantages are also obvious. In the case of high user dynamics, it is easy to lose lock.

② The noise bandwidth of the frequency-locked loop is wide. The frequency-locked loop can generate a signal with stable frequency error. It has a strong tolerance to dynamic stress. It can track low-power signals even when the noise is strong, and is insensitive to data bit jumps. However, the tracking accuracy is low, and it is difficult to obtain accurate carrier phase values.

In the case of high dynamics and low signal-to-noise ratio situation, the use of a frequency-locked loop can lock the signal firmly, which is convenient and fast to pull in the signal; in the case of low-dynamic situation, the use of a phase-locked loop can track the signal more closely and obtain a more accurate carrier phase value [6]. Based on these, this article discusses a compound loop that combines a frequency-locked loop and a phase-locked loop to track the signal.

In the composite loop, the phase-locked loop and the frequency-locked loop are not independent of each other. The second-order frequency-locked loop is usually used to assist the third-order phase-locked loop to achieve tracking. The principle structure is shown in Fig. 4.

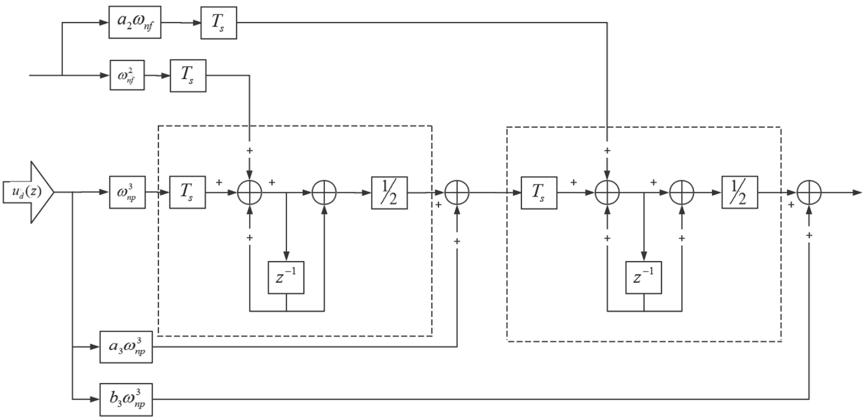

**Fig. 4.** The structure diagram of the combined loop of the second-order frequency-locked loop and the third-order phase-locked loop

The design has better flexibility. First of all, a rough carrier Doppler frequency shift estimate is obtained after the received signal acquisition. In the initial stage of tracking, due to the inaccuracy of the carrier Doppler shift value, it is difficult to directly use the phase-locked loop to quickly pull into the frequency lock range, and it may cause loss of lock. In this case, the frequency-locked loop can lock the signal more firmly, and can pull into the frequency locking range faster than a phase-locked loop. Therefore, select the pure frequency-locked loop when starting tracking, until the signal is drawn into the stable tracking state. Since the output phase measurement accuracy of the pure frequency-locked loop is low, the carrier loop is gradually transferred from the pure FLL to the FLL assists PLL, and finally enter the mode of the pure phase-locked loop. The pure phase-locked loop can track the signal more closely, and the accuracy of the output phase value has also been improved. In addition, when the phase-locked loop loses lock, the carrier loop can be switched to a pure frequency-locked loop, and the above process is repeated to maintain signal tracking.

### 3.3 Code Tracking Loop

The function of the code tracking loop is to track the ranging code phase values of the received signal, and adjust the copied ranging code phase by the ranging code generator according to the obtained code phase value until the copied ranging code is the same as the received signal. The ranging code can be completely stripped after multiplying. Usually delay locked loop (DLL) is used to realize code tracking. The general code tracking loop structure is shown in the Fig. 5.

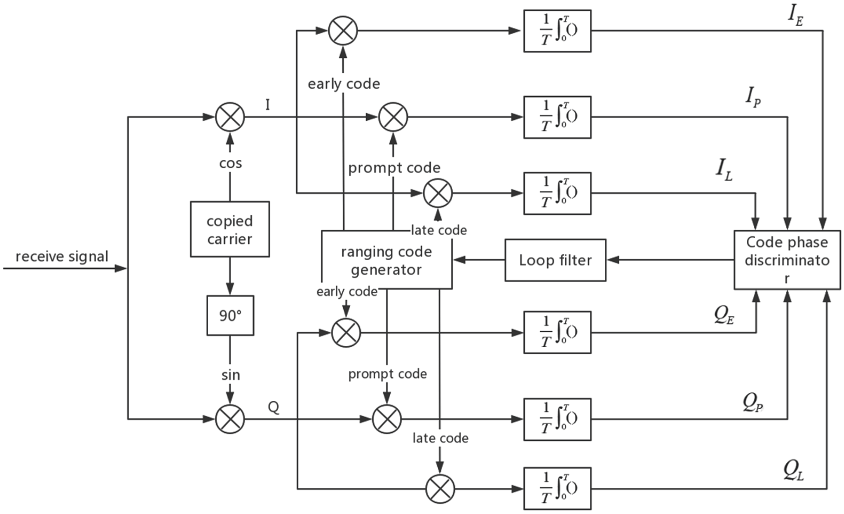

**Fig. 5.** The general code tracking loop structure

The carrier generator is used to generate the copied sine-cosine carriers with frequency close to the intermediate frequency. Then the ranging code generator is used to generate the copied ranging codes with certain code phases of the satellite. Subsequently, the received signal is multiplied and mixed with the sine and cosine carriers respectively, where the sine branch is an in-phase branch (I branch), and the cosine branch is an orthogonal branch (Q branch). The mixed signal is correlated with the copied ranging code. The ranging code generator replicates three codes with different phases, Early, Prompt and Late Code [9]. The expression is as follows.

$$\begin{array}{l} x_E(t) = C(t - \tau + \frac{d}{2}) \\ x_P(t) = C(t - \tau) \\ x_L(t) = C(t - \tau - \frac{d}{2}) \end{array} \tag{7}$$

In the code tracking loop, there are many forms of code phase discriminators. Common discriminators are shown as follows (Table 3).

**Table 3.** Common phase discriminator algorithms

| Discriminator Algorithm | Characteristic |
|---|---|
| $D = I_E - I_L$ | This algorithm is the simplest discriminator, no Q branch is required, but it has strict requirements on the carrier tracking loop |
| $D = \frac{(I_E^2 + Q_E^2) - (I_L^2 + Q_L^2)}{(I_E^2 + Q_E^2) + (I_L^2 + Q_L^2)}$ | Universal lead-lag energy difference discriminator, performance is still good when the symbol difference is greater than 1/2 symbol |
| $D = (I_E^2 + Q_E^2) - (I_L^2 + Q_L^2)$ | Lead-lag energy difference discriminator, the output at the symbol difference of ±1/2 symbol is almost the same as the first discriminator algorithm |
| $D = I_P(I_E - I_L) + Q_P(Q_E - Q_L)$ | This algorithm requires the output of 6 integrator, which requires a large amount of calculation |

## 3.4 Results of Tracking and Navigation Messages Demodulation

The BDS B1I signal parameters are the same as shown in Table 4.

**Table 4.** BDS signal parameters

| | |
|---|---|
| Satellite number | 31 |
| The code phase of the signal source | 1000 |
| Carrier doppler shift of signal source | 4700 |
| The initial carrier phase of the signal source | 0 |
| The signal-to-noise ratio of the signal source | 5 dB |

① The carrier loop is FLL, using a four-quadrant arctangent frequency discriminator algorithm.

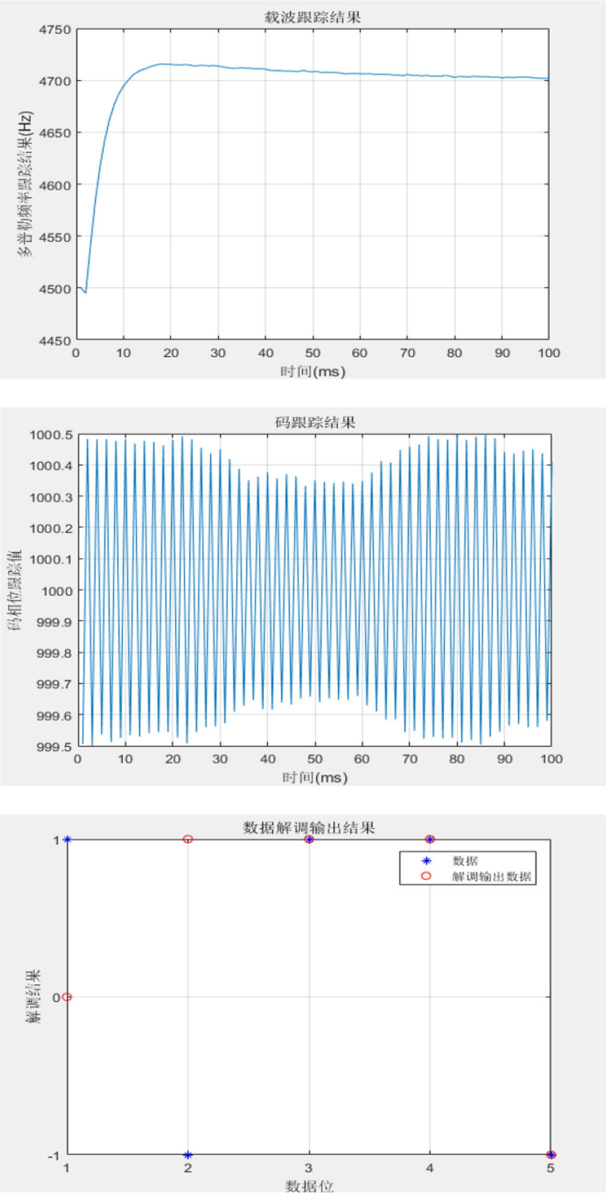

**Fig. 6.** The carrier loop is FLL

From the above figure, we can see that using the FLL loop can get a stable Doppler frequency shift output and code phase tracking value, but it takes a longer time to track to a stable state (Fig. 6).

② The carrier loop is PLL, which uses a two-quadrant arctangent phase detector algorithm (Fig. 7).

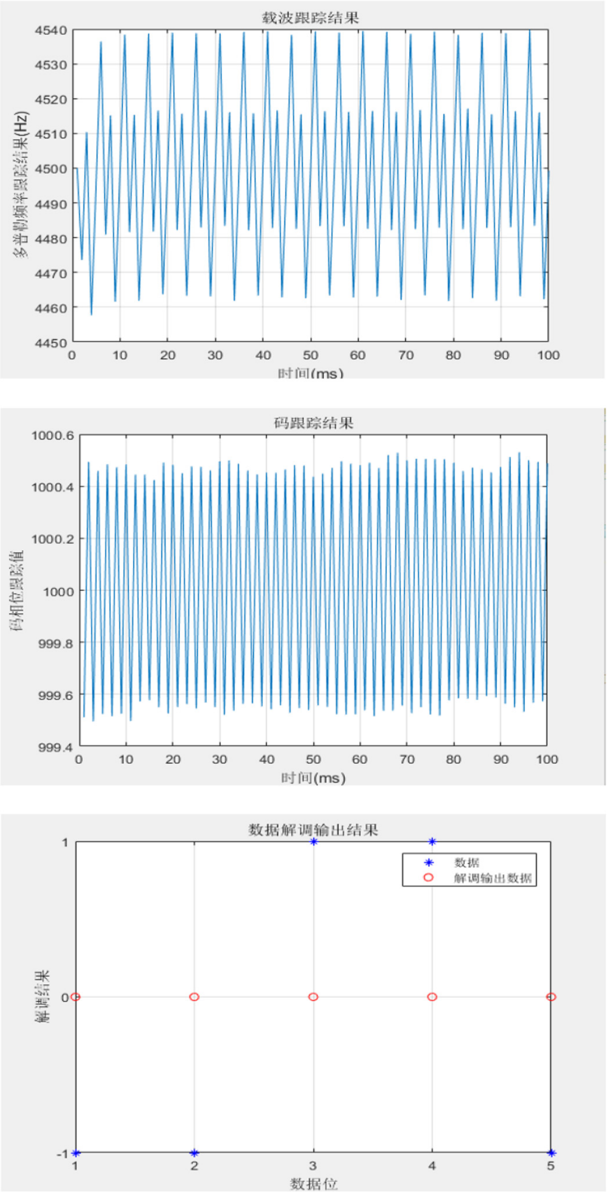

**Fig. 7.** The carrier loop is PLL

From the above figure, we can see that using the pure PLL loop will cause the carrier loop to lose lock. The stable Doppler shift output and the demodulated output data cannot be obtained.

③ The carrier loop is the second order FLL to assist the third order PLL composite carrier loop. The four-quadrant arctangent discriminator is used in the FLL and the two-quadrant arctangent discriminator is used in the PLL (Fig. 8).

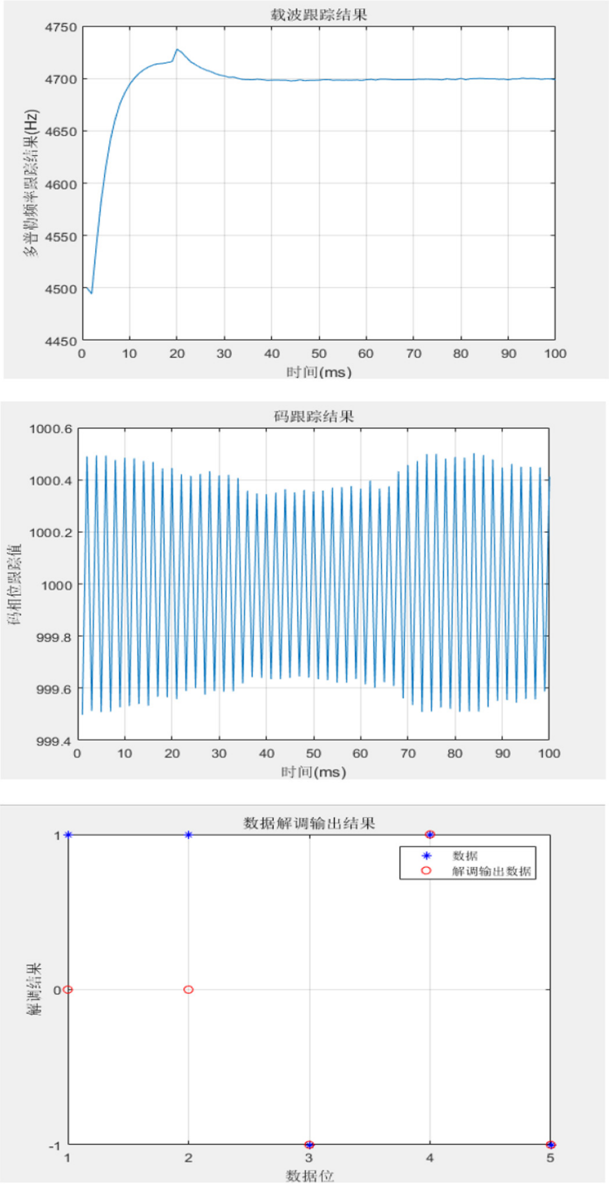

**Fig. 8.** The carrier loop is FLL to assist PLL

From the above figure, we can see that using the FLL and PLL combined loop can get a stable Doppler frequency shift output and code phase tracking value. What's more, it takes less time to reach stability.

## 4 Conclusion

Aiming at the tracking part of B1I navigation signal, this paper analyzes three different carrier loops and compares their performance. The simulation results show that using the FLL and PLL combined loop can get a stable Doppler frequency shift output and code phase tracking value. What's more, it takes less time to reach stability.

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