A Simple and Reliable Acquisition Algorithm for Low-Orbit Satellite Signal

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Abstract. In recent years, the global low-orbit communication and Internet constellation have entered a period of vigorous development. Low-orbit satellites have the advantages of high landing level and fast satellite geometry change, and the enhancement function of low-orbit navigation can complement the current mid-high-rail GNSS implementation and promote the deep integration of navigation communication, which is an important direction for the future development of the navigation system. Hongyan Navigation System is a low-orbit mobile communication and broadband internet constellation independently developed by China, which integrates navigation enhancement functions, and has real-time communication capability in full-time and complex terrain conditions to provide users with real-time global data communication and integrated information services. However, the Hongyan satellite has the characteristics of fast moving speed, short single-visible time, and greater doppler dynamics received by the users, which is not suitable for the traditional capturing methods. Therefore, it is of great research value and practical significance to study the Hongyan navigation signal. This paper studies the spread spectrum modulation and the synchronous acquisition of the transmitting signal based on the Hongyan constellation. On the Matlab platform, the excellent characteristics of the transmission signal of Hongyan system and the time-sequence capture method are verified.

Keywords: Hongyan navigation enhancement system · Low-orbit communication · Direct sequence spread spectrum · Code acquisition

1 Introduction

In modern times, the development of the Internet faces serious challenges such as scalability, security, mobility, controllability and manageability. In the future, the network will develop in the direction of deep integration with the real economy and the integration of communication and navigation functions is the construction direction of satellite navigation system in the intelligent era, aiming to establish a converged network architecture of sea, land and air to support the development of communication, navigation and surveillance network applications.

Global navigation satellite system receivers play a crucial role in variety of fields including navigation, positioning, and civilian surveying areas [1, 2], but due to the

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natural vulnerability of GNSS, the application in complex environments may be limited, and the positioning accuracy may be reduced or even unable to be located [3, 5]. In order to meet the higher requirements of precision, integrity, continuity, availability and other performances, various enhanced navigations have been generated on the basis of basic GNSS systems, and global low-orbit communication and internet constellation have become a research hotspot [6]. Low-orbit satellites, as space-based monitoring stations combined with GNSS and LEO satellites, can significantly improve the accuracy of precision single-point positioning and significantly improve the convergence of precision single-point positioning [7]. Low orbit satellite can also be used to enhance RTK, which can improve the speed of long baseline fuzziness calculation and fixed success rate, and can serve high-precision industries such as surveying and mapping, ocean and fine agriculture.

The ‘Hongyan Project’ of the Aerospace Science and Industry Group is based on global coverage assurance, national aviation and navigation applications, and mainly uses the downlink L-band communication link of Hongyan to broadcast real-time navigation enhancement information such as precise orbit, clock difference and code deviation, and provides global precise single point positioning service [8, 9]. The overall goal is to build a real-time, high-precision, space-based, low-track navigation enhancement system around 2021, that provides global military and civilian users with dynamic decimeter-level, static centimeter-level positioning and global seamless, fast Internet communication services.

However, the research of low-orbit satellite constellation on the user receiving terminal also increases the following difficulties: low-orbit satellite has low orbit, fast motion speed, short single-star visibility time, larger doppler dynamics received by the user, which put forwards higher requirements for signal acquisition and tracking. Therefore, it is necessary to provide more studies on the synchronization of Hongyan downlink signal. We aim to test the feasibility of the Hongyan spread system and simulate the code capture of the signal using accurate, controllable and reproducible simulation signals to develop and verify the “Hongyan Constellation” hardware receiver, enabling the development time and efficiency of the receiver to be guaranteed. The research of this project will help accelerate the development of China’s enhanced navigation technology, the construction of high-precision integrated PNT, deeply integrated system data fusion technology of GNSS/INS deeply integrated navigation under the complex environment and synchronization between the GNSS systems and INS system. The research results will be used in air-sea surveillance, aircraft precision approach and other fields.

The structure of the paper is as follows: in Sect. 2, direct sequence spread system model of “Hongyan Constellation” and the methods of code synchronization are presented. Section 3 illustrates and analyzes the simulation results. Section 4 summarizes the conclusions.

2 Materials and Methods

2.1 The Composition and Principle of Direct Sequence Spread System

Hongyan Constellation is a typical direct sequence spread spectrum system, it’s communication model is presented in Fig. 1.

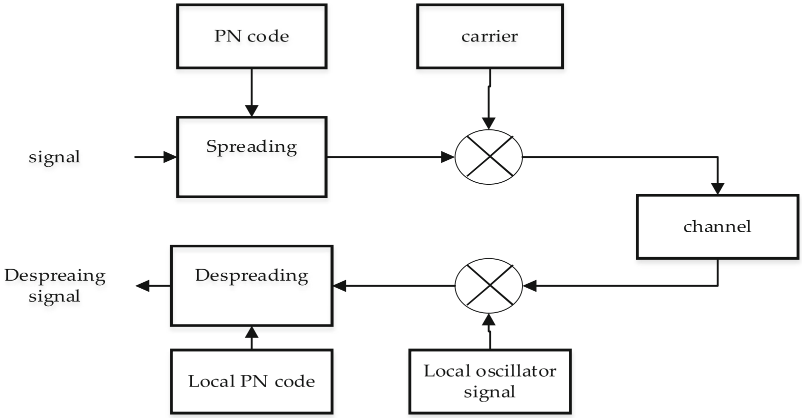

Fig. 1. Direct sequence spread spectrum system communication model

The system consists of a transmitting part and a receiving part. Generally speaking, its working mode is as follows:

The binary information code sequence that is input at the transmitting end is modularly added with the high speed code sequence to generate a spreading sequence with the same rate as the pseudo random code rate. Obviously, the bandwidth of the spreading sequence is higher than the original information bandwidth, thus completing the spectrum expansion of the information. Then, the spread spectrum sequence is subjected to carrier modulation, and the obtained radio frequency signal is amplified by power amplification. At the receiving end, the received spread spectrum signal is amplified by power and sent to the mixer. In the mixer, the signal is multiplied by the carrier, the signal is down-converted to the baseband, and the baseband signal is sent to the demodulator through the baseband filter to complete the demodulation. And then the demodulation signal is multiplied by the local PN code sequence to complete the dispreading. This restores the original data information [10].

Taking the PSK signal as an example, the signal of the direct expansion system can be expressed as:

$$s(t) = \sqrt{2P}d(t)c(t)\cos(w_0 t + \theta_0) \tag{1}$$

where $d(t)$ is the information data, and $c(t)$ is the spreading code, which is a rectangular wave signal a value of $+1$ or -1.

At the receiving end, it is assumed that the received signal contains useful signals and noise introduced by the system, which can be expressed as

$$s'(t) = \sqrt{2P}d(t)c(t)\cos(w_0 t + \theta_0) + n(t) \tag{2}$$

In the despreading process, the locally generated spreading code $c(t - \tau)$ is used to correlate with the received signal, and the related signal is expressed as

$$s'_c(t) = \sqrt{2P}d(t)c(t)c(t - \tau)\cos(w_0 t + \theta_0) + n(t)c(t - \tau) \tag{3}$$

In the case where the local code phase and the code phase in the signal are aligned,$c(t)$ is the same as $c(t-\tau)$,$c(t)c(t-\tau)=1$, so $d(t)$ can be resumed after demodulation.

Direct Sequence Spread Spectrum system is the most important application in the military communication. The interferences encountered in practical applications cover white noise interference or broadband noise interference, partial frequency band noise interference, single frequency and narrowband interference, pulse interference and multipath interference. Spreading signals are inevitably subject to noise interference during transmission, generally additive white Gaussian noise or band-limited white noise. The correlator input noise power is

$$N_i = n_0 B_c \tag{4}$$

Wherein, the unilateral power spectral density of the noise is n_0, B_c is the spread spectrum signal bandwidth, thus the correlator output noise power is

$$N_0 = \frac{1}{2\pi}\int W_a G_{nI}(w)dw \tag{5}$$

where W_a is the information bandwidth of $2\pi B_a$. Considering that $B_a << B_c$ and the noise power is near f_I, we can know $G_{nI}(w)$ is approximately K_{n0}, where K is a constant related to the modulation scheme. For PSK modulation, $K = 0.903$, so

$$N_0 = \frac{1}{2\pi}Kn_0 W_a = Kn_0 B_a \tag{6}$$

Since the amount of information before and after despreading is constant, the processing gain of the direct-spreading system for white noise interference is

$$G_{pn} = N_i/N_0 = B_c/KB_a = G_p/K \tag{7}$$

2.2 Code Synchronization

The acquisition based on code synchronization is essentially the reception process of despreading and demodulation. Since its purpose is to perform time synchronization, it is only necessary to find the position of the correlation peak, and it is not necessary to use the demodulation and decoding link to extract the information carried by the carrier phase. Therefore, a relatively simple method is often used to eliminate the influence of the phase offset. The transmitting end modulates the synchronized code sequence, and the receiving end receives the mutually orthogonal I and Q baseband signals by orthogonal down-conversion. According to the trigonometric identity, the I and Q the two baseband signals are matched by the matched filter and the output correlation values are squared, and the obtained sum value no longer contains the carrier random phase information. Choosing this value as a statistical decision eliminates the effects of phase shift. Finally, it is compared with a certain threshold value to make a capture decision [11, 12]. The capture decision methods adopted in this paper are all based on time-domain analysis for serial search. The block diagram of serial capture principle circuit is shown as Fig. 2.

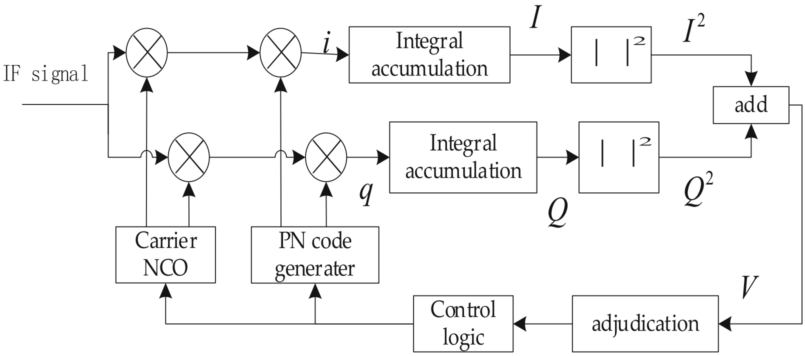

Fig. 2. Serial capture principle circuit

After the signal received by the antenna is down-converted, the digital intermediate frequency signal after sampling at the sampling interval T_c is

$$S(n) = aD(n)C(n)\exp\ j[2\pi(F_{IF} + F_D)nT_C + \phi] + n \tag{8}$$

In the formula, the amplitude of the received signal is a, the navigation message data code is D_n, C_n is the C/A code, F_{IF} is the intermediate frequency, F_D is the doppler frequency, ϕ is the initial phase of the received signal and n is the noise, which is the summary of two white noises n_I and n_Q.

After demodulating and dispreading with the use of local carrier NCO and pseudo-code generator respectively, coherent accumulation is performed, and the integrated values of I and Q are calculated as follows

$$I(n) = AD(n)R[\varepsilon(n)]\mathrm{sinc}(\pi F_D T)\cos(\phi_e) + n_I \tag{9}$$

$$Q(n) = AD(n)R[\varepsilon(n)]\mathrm{sinc}(\pi F_D T)\sin(\phi_e) + n_Q \tag{10}$$

Wherein, A is the signal amplitude, ε_D is the chip phase difference, F_D is the carrier frequency difference, $R[\varepsilon(n)]\mathrm{sinc}(\pi F_D T)$ is the frequency difference, $\phi_e = 2\pi F_D(n - 1/2)T + \varphi$ is the carrier phase difference, φ_n is the initial phase difference. Regardless of noise, we can develop (11) from (9) (10).

$$\sqrt{I^2(n) + Q^2(n)} = aR[\varepsilon(n)]|\mathrm{sinc}(\pi F_D T)| \tag{11}$$

The above equation shows that the phase difference between the received carrier and the replica carrier does not affect the non-coherent detection. If the number of non-coherent integrations is N_{nc}, the detection amount can be expressed as:

$$V = \frac{1}{N_{nc}} \sum_{n=1}^{N_{nc}} \sqrt{I^2(n) + Q^2(n)} \tag{12}$$

The time domain serial capture algorithm is the most basic capture algorithm, and its hardware design is very simple.

3 Results and Discussion

The Hongyan first star downlink L-band signal is a continuous direct sequence spread spectrum signal. There are two rate modes, which is shown as Table 1. Each rate mode includes three rates, and the three rates have a spreading ratio of 125/62.5/31.25 times. In order to ensure that the symbol is complete, we divide the ratio of 62.5 into 62/63 and 31.25 is divided into 31/31/31/32.

Table 1. Hongyan first star downlink L-band signal parameters.

Center frequency (MHz)	Code length	Code rate (Mbps)	Symbol rate
1521.5 MHz	125	Mode 1:1.2	Rate 1: 9.6/19.2/38.4 Kbps
		Mode 2:0.15	Rate 2: 1.2/2.4/4.8 Kbps

Using Matlab as a platform, the simulation of the first star downlink signal of Hongyan Constellation was carried out. According to the signal parameters, we selected the code length of 125, the code rate of 1.2 MHz and the information rate is 9.6kbps during our simulation.

3.1 Simulation of Transmitted Signal

Generation of Information Code

To build a direct expansion system, we firstly use a small number of symbols to generate an information code sequence. Let the information code rate be 9.6 kHz, the sampling frequency be 7.68 MHz, and the information code length be 20, then each information code contains 800 sampling points. The information code is shown as Fig. 3.

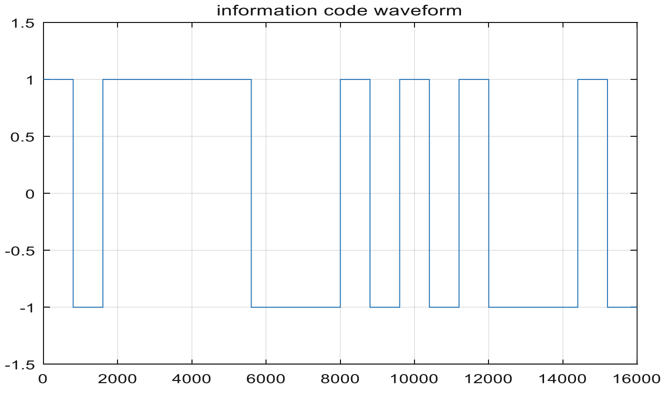

Fig. 3. Information code waveform

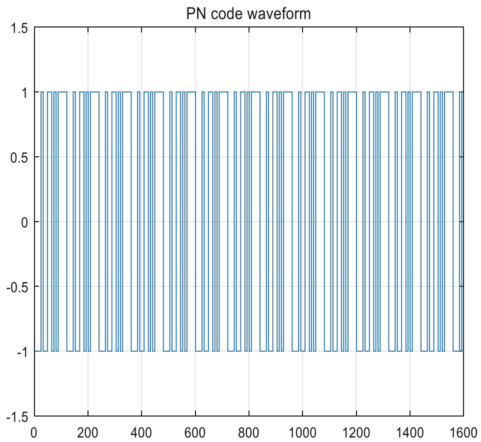

Fig. 4. Gold code waveform

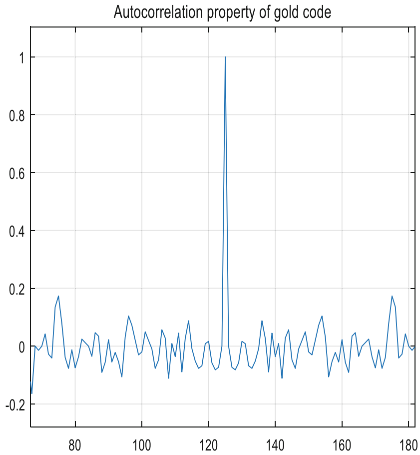

Fig. 5. Autocorrelation property of gold code

Generation of Pseudo-Random Code Sequences

The codeword of the spreading code of Hongyan system is generated by the gold code, which is obtained by two m sequences of the same length and the same rate but of different code words.

The generator polynomial is:

$$f_1(\mathrm{x}) = 1 + x + x^2 + x^3 + x^5 + x^6 + x^7 \tag{13}$$

$$f_2(\mathrm{x}) = 1 + \mathrm{x}^4 + x^5 + x^6 + x^7 \tag{14}$$

The initial phase of G1 is: [1 1 1 0 0 1 1].

The initial phase of G2 is: [0 1 0 1 1 1 0].

The pseudo-code is shown as Fig. 4. The code frequency is set to 1.2e6, so each information code contains 125 pseudo codes, that is, the generated pseudo random code sequence contains 2000 symbols.

From Fig. 5, it is clear to see that gold code has a sharp autocorrelation function to facilitate capture tracking and fast synchronization.

Spreading and Modulation

Multiply the sampled information code sequence and the pseudo-random code sequence corresponding point, the spread spectrum signal is generated in Fig. 6. Then we obtained the modulated wave shown as Fig. 7 by multiplying the corresponding point of the carrier and the spreading signal.

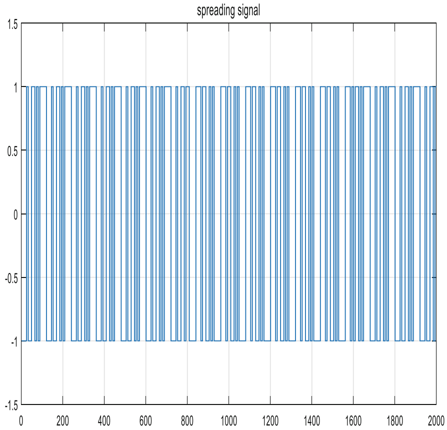

Fig. 6. Spread spectrum signal

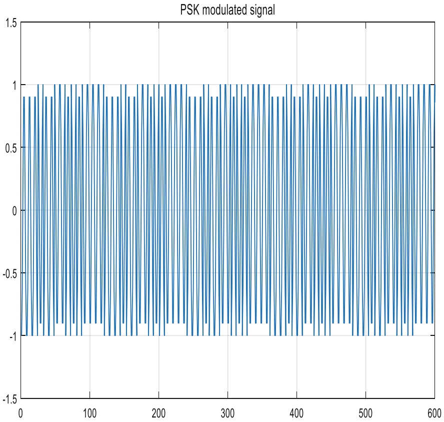

Fig. 7. PSK modulated signal

3.2 Simulation of Received Signal

PSK Demodulation

Demodulation is equivalent to the inverse process of modulation, and it includes generating a local oscillator in phase with the same frequency of the carrier and then removing the high frequency component through the low pass filter, ready for the next dispreading. Demodulation signal is shown as Fig. 8.

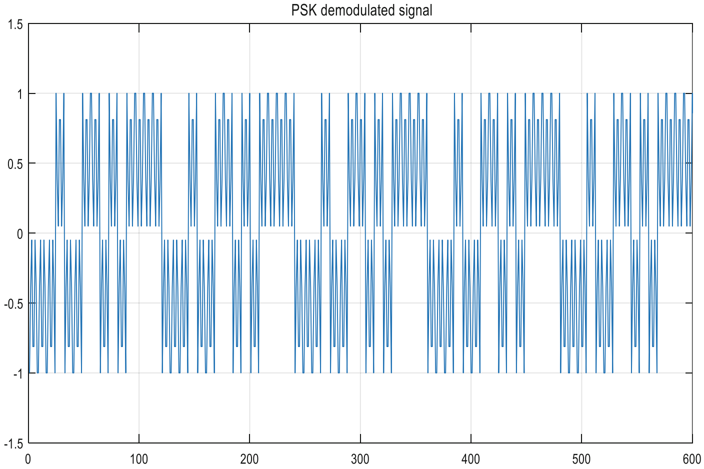

Fig. 8. Demodulated signal

Despreading

After the modulated signal is filtered by a low-pass filter, by multiplying the local pseudorandom sequence synchronized with the originator with the corresponding point of the demodulated sequence, the dispreading signal was restored. As can be seen from Fig. 9, the restored information code is basically the same as the source information code.

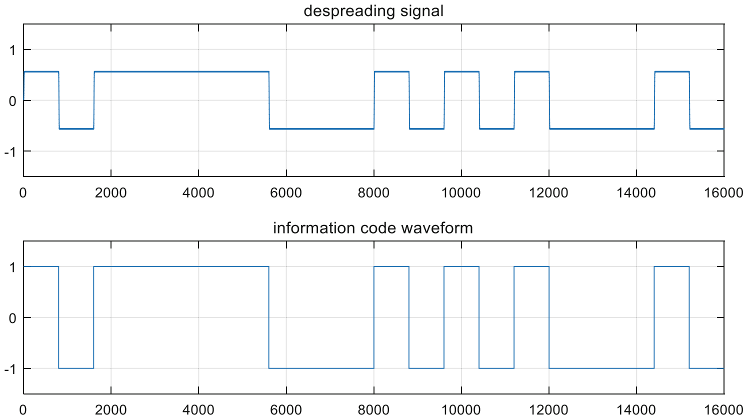

Fig. 9. Comparison of restored signal and information code

However if the noise is added, there is a big difference between the output code and the original information code, mainly because the local code inevitably has an unsynchronized phenomenon during dispreading. Figure 10 shows the comparison of despreading signal and information code, there are a large number of burrs in the dispreading signal but the shape is roughly the same as the information code.

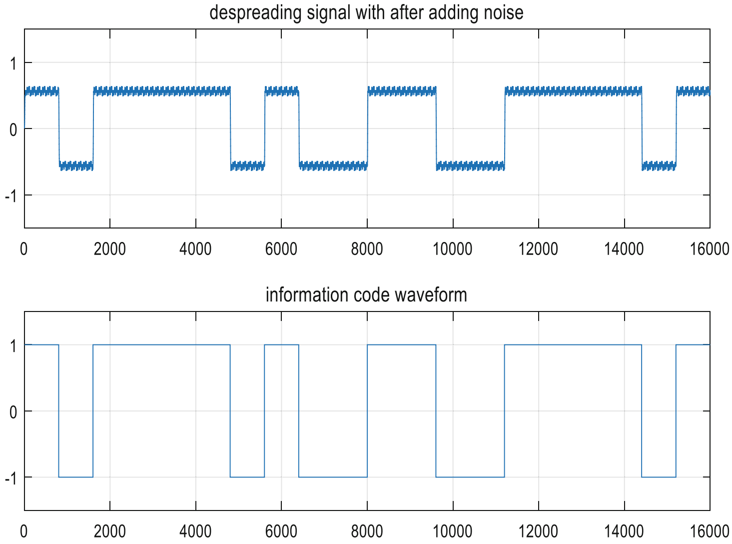

Fig. 10. Comparison of despreading signal and information code

3.3 Time-Domain Analysis for Serial Search

In the process of code synchronization, equivalent to two codes sliding to each other, when the two code sequences coincide, the sliding stops, the capture is completed, the normal code speed enters, and the tracking phase is synchronized.

The local controlled pseudo random code is delayed by 50 chips with the gold code. As is revealed as Fig. 11, when the local controlled PN code slided 118 chips, the capture loop completed the synchronization of the spreading code. Analysis above demonstrates the applicability of time domain serial code capture to Hongyan system.

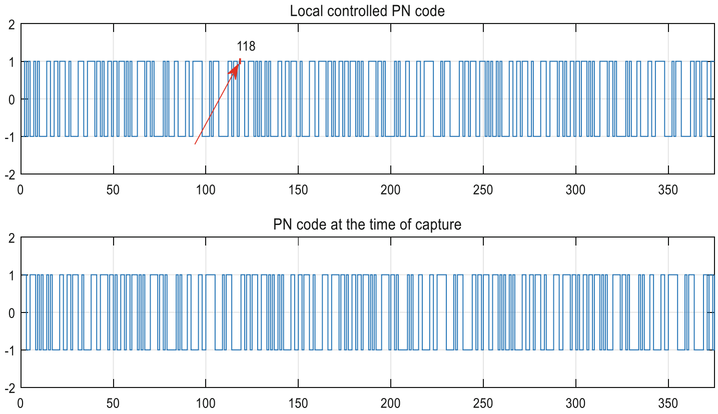

Fig. 11. The process of code synchronization

4 Conclusions

Based on the research of the downstream signal generation process and the principle of direct spread spectrum system of Hongyan constellation, this paper establishes the overall architecture of Hongyan downlink signal simulation implementation. Firstly, the pseudo-random code is generated and verified. On the basis of the correct and reliable pseudo-random code, the downlink signal of Hongyan constellation is simulated and generated, and the code synchronization is performed at the receiving end by time domain serial search. The results show that the simulation signal scheme is correct and reasonable, and the simulation implementation process is correct and credible. It has important theoretical and practical significance for studying the Hongyan navigation enhancement system.

Unfortunately, when the bit number of pseudo-code is large, the capture time of the time domain serial capture is too long. But this problem could be solved if we use FFT-based parallel capture method. Despite its insufficient aspects, this study can clearly illustrate the excellent characteristics of the downlink transmission signal of Hongyan navigation enhancement system and the time-sequence capture method can be used surefirely to simulate the Hongyan system. Based on the research of this paper, the enhancement of the Hongyan constellation combined with GNSS navigation will be summarized in our next study.

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