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Transceiver Pseudolite Carrier Frequency Self-Alignment Closed-Loop System

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Abstract Due to instability of a normal pseudolite, it is vital to ensure the signal transmitted by a pseudolite stable. In this paper, a carrier frequency self-alignment closed-loop system is designed for enhancing the stability of a transceiver pseudolite. Carrier frequency feedback is used to compensate for interference from external noise so that it can make the signal more stable. This system is able to be stable via the related root locus and bode diagram analysis. PID compensation is used to enhance transient-state and static-state performance of carrier frequency self-alignment closed-loop system. According to MATLAB Simulink simulation, carrier frequency self-alignment is achievable and it can suppress external noise interference, which makes the signal more stable.

Keywords GPS pseudolite · carrier frequency loop self-alignment closed loop · tracking control · PID compensation

1 Introduction

It has been widespread to use GPS to locate one's position. Despite this, GPS is still susceptible to a variety of external interferences, which can result in decreasing positioning accuracy and even be unavailable. Therefore, there are some researches about integrity and vulnerability[1].

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Using a pseudolite can both improve the GPS positioning accuracy and establish an indoor positioning system individually[2]. However, those must be based on a decent performance pseudolite. Otherwise, in contrast, it will decrease the positioning accuracy. Thus, pseudolites with a decent performance are required.

The basic principle of a GPS pseudolite is that the GPS pseudolite transmits a simulated GPS signal, which is a ground-based argument device in fact[3].

The GPS satellite itself carries many high accuracy and precision devices. Also, its clock bias can be compensated for by the relevant navigation message provided by many GPS ground observation posts (GOP) when positioning. Nonetheless, GPS pseudolites are much simpler than it. An important reason is cost, which causes a number of problems. For instance, every GPS satellite is equipped with the sophisticated atomic clock as its clock reference but every GPS pseudolite usually just uses an ordinary quartz crystal oscillator instead. Then, the clock frequency in the GPS pseudolite will be less stable compared with a GPS satellite. Thus, some relevant measures must be taken to remain the GPS pseudolite stable[4]. At the same time, the GPS receiver cannot treat the signal from the pseudolite as well as an actual GPS satellite.

This baseband signal is generated in the FPGA and navigation messages are generated in the STM32 of the pseudolite. Then, it uses AD9361 radio frequency (RF) agile transceiver to upconvert and transmit the signal.

If the pseudolite is able to receive the simulated GPS signal transmitted by itself and then analyze its signal quality and compensate for the carrier frequency drift, the simulated GPS signal becomes more stable.

Therefore, we need to analyze the simulated GPS signal transmitted by a single pseudolite to understand the internal operating state and make some proper real-time adjustments such as compensating for carrier frequency drift.

The transmitter and receiver inside the pseudolite will form a closed-loop system. In contrast, a common pseudolite which is not equipped with a receiver is an open-loop system. The receiver loop inside the pseudolite is feedback of the signal and it is just similar to a common universal receiver. Nevertheless, it must have good robustness avoiding losing lock on the signal. Then, some parameters about the simulated GPS signal can be obtained from it. If the carrier frequency drifts, the feedback path can acquire it and adjust phase of the numerically controlled oscillator (NCO) properly inside

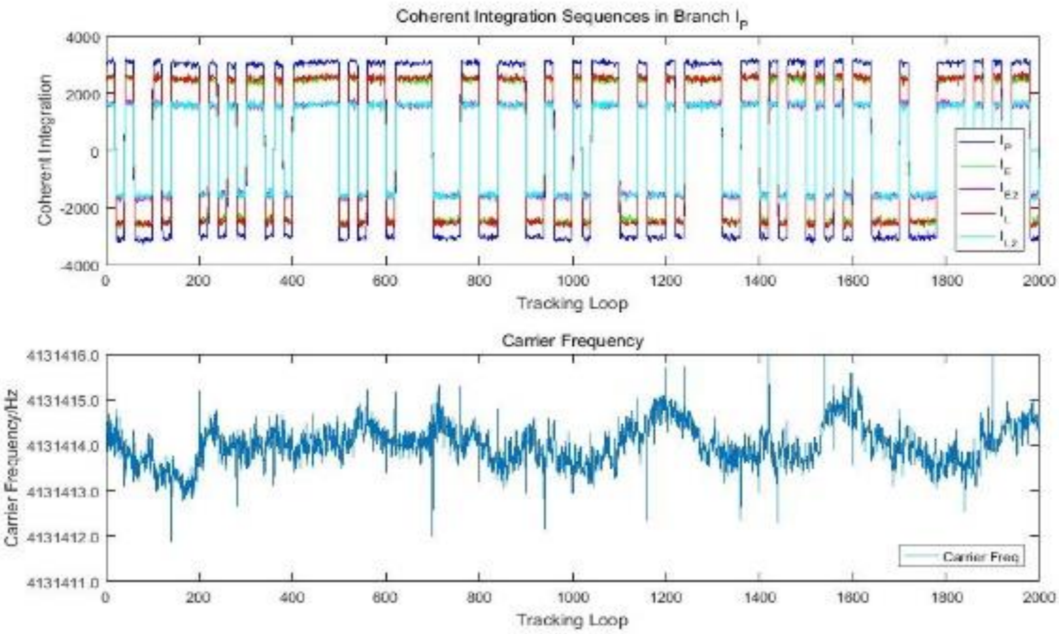

Fig. 1 coherent integration and carrier frequency in the stable state

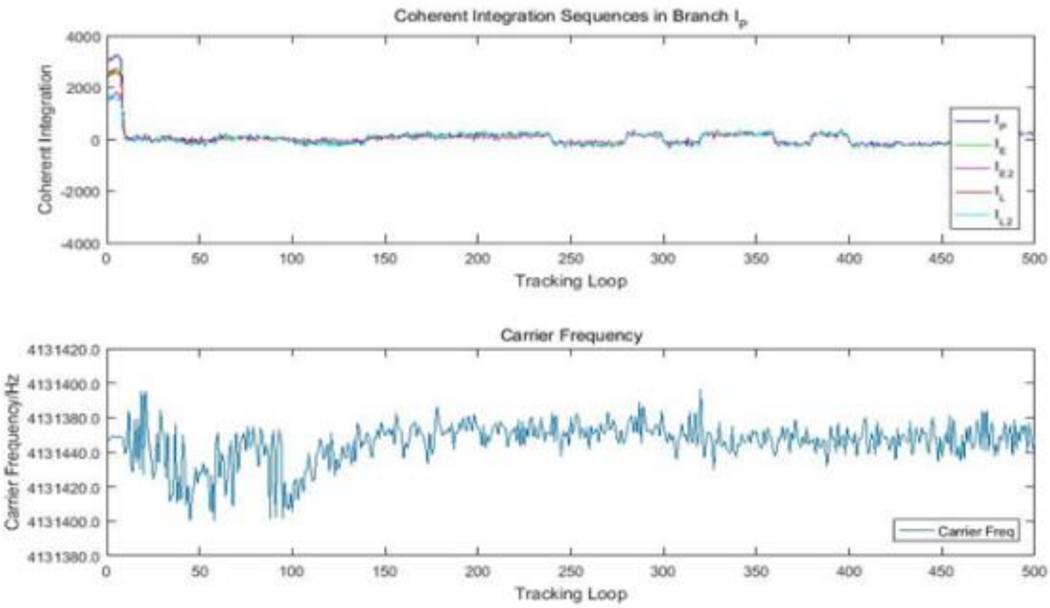

Fig. 2 coherent integration and carrier frequency in the metastable state

the transmitter to compensate for the frequency drift making the signal more stable. Code frequency drift and other parameters can be treated in a similar way. Thus, the signal transmitted by a closed-loop pseudolite will be more stable than that transmitted by an open-loop pseudolite.

We know that carrier loop is an independent loop in a receiver while code loop is assisted by carrier loop via a fixed amplifier. Thus, in this paper, we just study the carrier frequency self-alignment loop.

2 Signal Stability Problems in a Pseudolite

We can use GPS software receiver to obtain more details about a single GPS pseudolite via the intermediate frequency (IF) data file collected by IF sampler. In order to analyze the signal quality, some special functions must be added into the GPS software receiver. Then, we can use that to analyze signal quality and obtain the result of parameters such as carrier frequency and so on.

The signal analysis is from IF data file, so it is post processing. We can find problem that the signal transmitted by an open-loop pseudolite may be unstable.[5]

2.1 Stable signal and metastable signal

Sometimes, the receiver fails to tracking the signal transmitted by pseudolite. There are many symptoms such as unstable carrier frequency, unstable code phase, BPSK modulation failure and so on.

The carrier loop is a more precise loop when compared with code phase and carrier frequency is higher than code frequency. Thus, carrier loop is easier to lose lock on the carrier.

In Figure 1, we can see that the carrier frequency was stable at the acquisition frequency of the digital IF sampler and the oscillation did not exceed plus or minus 1 Hz and burrs did not exceed plus or minus 2 Hz generally. The pseudolite signal was stable at that time and the coherent integration in every branch sequence was in the normal state.

In Figure 2, we can see that the carrier frequency was unstable. Especially, it moderately oscillated between loop 0 to 150 less than 25Hz and 0.4Hz/ms. After that, it tended to be stable from loop 200 on and became oscillation again with more than 0.5Hz/ms. Nevertheless, its oscillation amplitude was still greater than that in the stable state. Therefore, we call it metastable state.

When it moderately oscillated, the coherent integration oscillated around zero value. To a universal receiver, it means nearly losing lock on this signal and navigation message cannot be solved correctly. In this state, the universal receiver should abandon using this pseudolite because it is malfunction.

This is because the code phase tracking is basically stable, but the carrier tracking becomes unstable, which indicates that the carrier in the signal becomes unstable first. An unstable carrier frequency can affect the code loop tracking condition so that the difference between and will be increased a little than those in the normal state and the accuracy and precision of will be decreased.

In Figure 3, considering the navigation message bit reversal, of the signal was about 58dB in the stable state while 33dB in the metastable state. In the prophase of the metastable state, was much lower because of unstable oscillation. Thus, the quality of the signal decreased and reliability became worse.

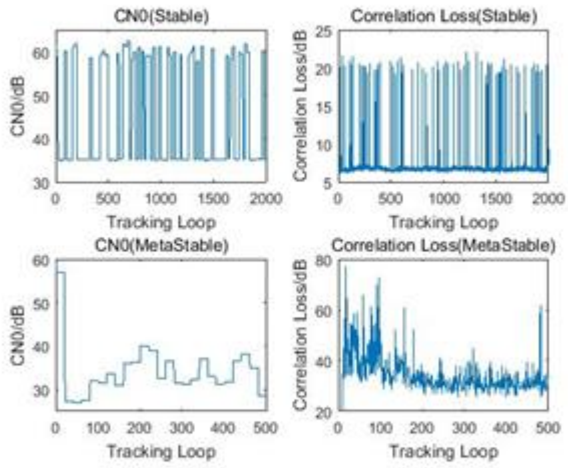

Fig. 1 carrier noise ratio in the stable and metastable state

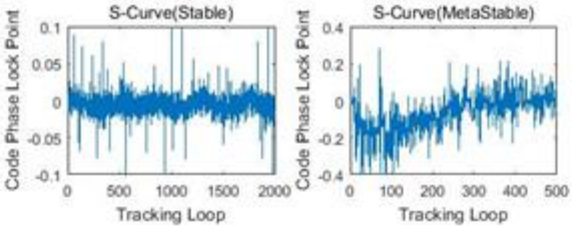

Fig. 2 code phase lock point in the stable and metastable state

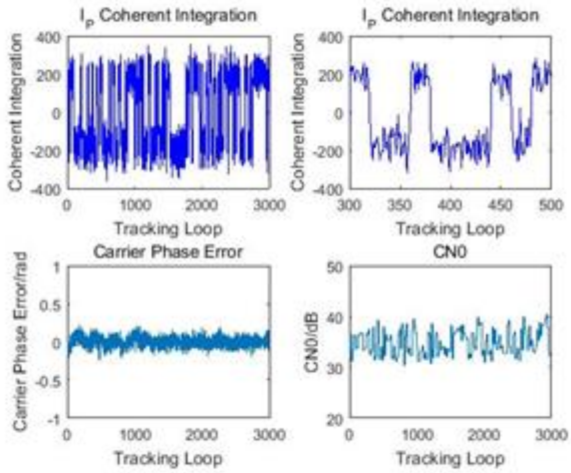

Fig. 3 signal in the metastable state

In Figure 4, the code phase lock point was around zero value in the stable state. However, the code phase lock point oscillated off zero value in the prophase of the metastable state. It indicates that the code loop also tended to be unstable.

2.2 Unstable signal

Sometimes, the carrier frequency severely oscillates even greater than 500Hz. It means that the signal cannot be used any more.

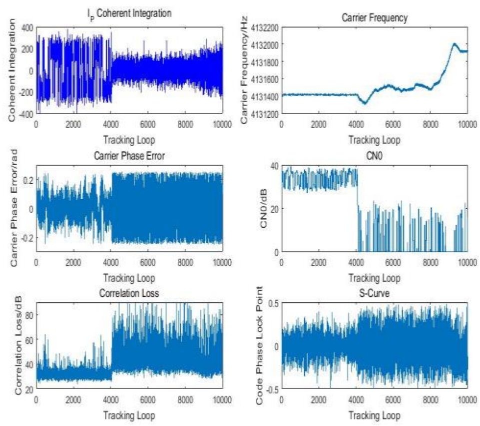

Fig. 4 severely carrier frequency oscillation

In, we can find that the carrier frequency severely oscillated after loop 4040 and was too low or even equal to zero. In this state, the tracking loop cannot track the signal properly. The coherent integration sequence can be considered as a random noise sequence, which the receiver cannot obtain any valid navigation messages with full of bit generation failure. Thus, the universal receiver should discard tracking this pseudolite or reacquire it immediately.

In order to avoid interfering positioning in this situation, checking and adjusting the carrier frequency is required or shut down the pseudolite and then reset immediately. Therefore, it is vital that a pseudolite which is able to transmit specific stable signal is in site.

3 GPS Pseudolite Receiver

The structure of the GPS pseudolite receiver is the feedback path of a carrier frequency self-alignment pseudolite, which can be divided into three stages: acquisition, tracking, bit and subframe synchronization. The receiver's position solution is not needed when it comes to signal quality analysis. Also, subframe synchronization is not needed in carrier frequency self-alignment closed-loop. In order to reduce computation load and accelerate operation, C/A code table is saved as a local file. When needed, it can be read by the program at a specific frequency[6].

3.1 Acquisition Stage

In the acquisition stage, parallel code phase search will be used.

Pseudo random noise (PRN) number of the pseudolite is set in the configuration by the operator in the pseudolite program so that we only need to use the two-dimension search including carrier frequency and code phase. The carrier frequency search range is 20kHz and the carrier frequency bin is 500Hz wide. The code phase range is 1023 chips and the code phase bin is 1chip wide. The receiver sample rate is 12.8MHz and the center frequency of local carrier wave is 1.6MHz, which can avoid the effect of the frequency mirror problem.

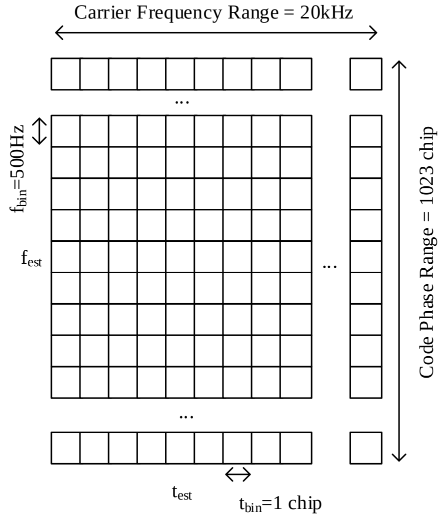

Fig. 5 two-dimensional search

We use the parallel code phase search to acquire the pseudolite signal. First, we need to operate two consecutive signals whose length both are 1ms in order to avoid signal level flipping caused by navigation message bit transition using the same frequency local carrier. Then, we can find the code phase peak value or maximum value in the result for both two signals and choose the signal whose peak value or maximum value is greater. If this peak value is higher than the acquisition threshold, we can conclude that the pseudolite signal is acquired successfully. Otherwise, we need to continue on the carrier frequency search by adjusting the local carrier frequency.

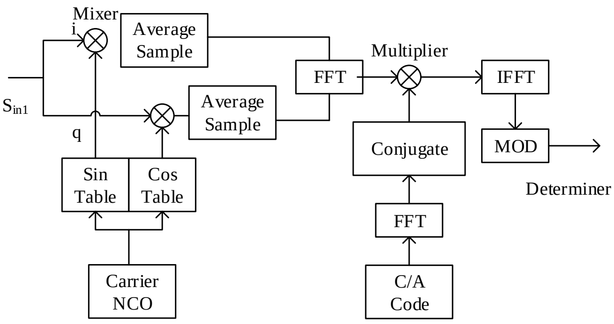

Fig. 6 parallel code phase search

3.2 Carrier Loop in Tracking Stage

The tracking stage includes a code loop and a carrier loop. The design principle is that the receiver should avoid tracking failure of the pseudolite signal, which also means that loop operation has good robustness and good transient-state performance. In this paper, only carrier loop is involved.

Phase locked loop (PLL) will be used in the carrier loop. PLL is a closed loop. In the forward path of PLL, there are two branches I and Q. There is a mixer, correlator, coherent integration in both branches. The outputs of those two branches are fed into a discriminator. In the feedback path, there is a second order loop filter and NCO.

First, signal will be mixed by the output of the NCO to remove the residual carrier. Then, correlator will remove the C/A code in the signal. At last, we can obtain the samples and coherent integration.

$$i(n) = s_{IF} u_{os}(n) \quad (1)$$

$$i_p(n) = \sum_{k=0}^{N-1} i(k) x(k-n) \quad (2)$$

$$I_p = \frac{1}{N_{coh}} \sum_{k=1}^{N_{coh}} i_p(nN_{coh} + k) \quad (3)$$

where S_{IF} is a signal segment acquired by a digital IF sampler, u_{os} is digital sine wave generated by the NCO, $x(n)$ is the C/A code sequence, k is current sample, N is the number of samples per C/A code period, N_{coh} is the number of coherent integrations. Coherent integration is also a low pass filter so that it can filter out high frequency noise.

The PLL discriminator is used to calculate carrier phase difference via the equation (4):

$$\phi_e = \arctan\left(\frac{Q_p}{I_p}\right) \tag{4}$$

In order to observe the carrier frequency, phase threshold of discriminator needs to be loose so that the PLL must need good robustness.

The structure of second order PLL loop filter is simple. Considering that the signal transmitted by a pseudolite is less stable than a real GPS satellite, we set noise bandwidth $B_l = 25$ Hz and damping ratio $\xi = 0.707$ due to the carrier frequency oscillation situation in Figure 2. According to the (5), we can find that eigenfrequency $\omega_0 = 47.133$ rad/s. We set the loop filter gain $K_f = 1$. Then, the loop filter transfer function becomes:

$$B_l = 0.53\omega_0 \tag{5}$$

$$F_{P2}(s) = \frac{\omega_0^2}{s} + 2\xi\omega_0 = \frac{2221.2}{s} + 66.5 \tag{6}$$

A third order PLL loop filter is needed for a good robustness receiver. We set noise bandwidth $B_l = 18$ Hz, filter constants $a_3 = 1.1$ and $b_3 = 2.4$ [7]. According to the (7), we can find that eigenfrequency $\omega_0 = 22.946$ rad/s. Its loop filter transfer function becomes:

$$B_l = 0.7845\omega_0 \tag{7}$$

$$\begin{aligned} F_{P3}(s) &= \frac{\omega_0^3}{s^2} + \frac{a_3\omega_0^2}{s} + b_3\omega_0 \\ &= \frac{12081.5}{s^2} + \frac{579.2}{s} + 55.1 \end{aligned} \tag{8}$$

The second order loop filter block diagram is[8]:

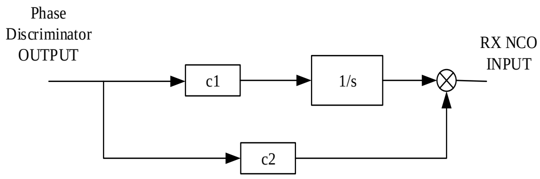

Fig. 7 second order loop filter block diagram

In Figure 9, $c_1 = \omega_0^2$ and $c_2 = 2\xi\omega_0$. However, due to the special structure in carrier frequency self-alignment closed-loop system compared with a normal receiver PLL, performance of third order PLL loop filter may be worse than second order PLL loop filter.

Considering that carrier frequency of the pseudolite may oscillate more than 25Hz and 0.5Hz/ms, we bring in frequency locked loop (FLL). A second order FLL is often used to assist a third order PLL and a first order FLL to assist a second order PLL. According to the frequency discriminator (9), we can combine FLL and PLL via a differentiator.

$$\omega_e = \frac{\phi_e(n) - \phi_e(n-1)}{t(n) - t(n-1)} \tag{9}$$

The block diagram of the second order PLL loop filter assisted with the first order FLL loop filter is[9]:

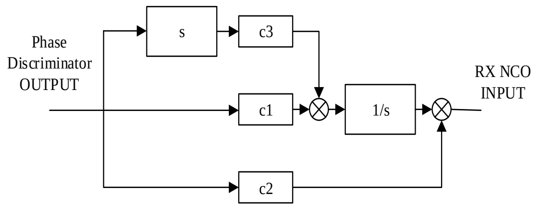

Fig. 8 second pll loop filter assisted with first fll block diagram

In Figure 10, $c_3 = \omega_0$.

Considering carrier frequency oscillation, we set noise bandwidth $B_l = 25$ Hz for first order FLL loop filter while $B_l = 18$ Hz for second order FLL loop filter. We can get the transfer function of the second order PLL loop filter assisted with the first order FLL loop filter and the third order PLL loop filter assisted with the second order FLL loop filter eventually.

$$F_{P2F1}(s) = \frac{\omega_0^2}{s} + (2\xi + 1)\omega_0 = \frac{2221.2}{s} + 113.8 \tag{10}$$

$$\begin{aligned} F_{P3F2}(s) &= \frac{\omega_0^3}{s^2} + \frac{(a_3+1)\omega_0^2}{s} + (b_3 + 2\xi)\omega_0 \\ &= \frac{12081.5}{s^2} + \frac{1105.7}{s} + 87.5 \end{aligned} \tag{11}$$

Carrier loop contains a loop filter, an RX NCO and a loop discriminator. The block diagram of carrier loop of the receiver is shown below.

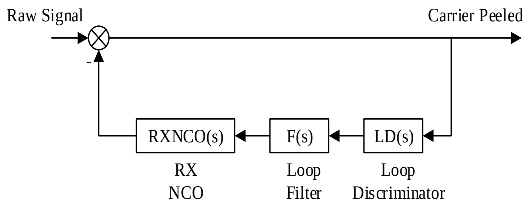

Fig. 9 receiver carrier loop block diagram

In Figure 11, $RXNCO(s)$ is transfer function of RX NCO, and we set its gain $K_n = 1$. $LD(s)$ is transfer function of carrier loop discriminator, and we also set its gain $K_{ld} = 1$. Thus, the total gain of the receiver loop is unit.

$$RXNCO(s) = \frac{1}{s} \tag{12}$$

$$LD(s) = 1 \tag{13}$$

4 Establishment and Analysis of GPS Pseudolite Carrier Self-Alignment Model

In this section, we will focus on the establishment of the GPS pseudolite carrier frequency self-alignment model first. Then, we will analyze closed-loop stability of this system and proportional-integral-derivative(PID) compensation will be brought in.

4.1 Establishment of GPS pseudolite carrier self-alignment model

When it comes to a normal universal receiver, its carrier loop is very stable and the frequency oscillation of local duplicated carrier is just within several Hertz. Therefore, once carrier loop is near losing lock on the carrier, the main problem is that the signal is unstable instead of receiver's malfunction. However, carrier frequency of the signal transmitted by a pseudolite often oscillates in a large scale due to poor stability of a crystal oscillator.

In order to solve that issue, the receiver loop is brought in, which is used to find the carrier frequency drift value via a loop discriminator inside the receiver loop. Then, the system can real-time adjust the carrier frequency of signal transmitted by the pseudolite effectively via the additional specific compensation method according to the carrier frequency drift value.

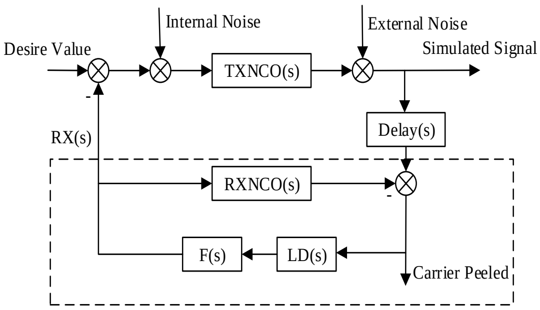

Fig. 10 pseudolite carrier frequency self-alignment closed-loop system block diagram

In Figure 12, $RX(s)$ is equivalent transfer function in feedback path of carrier frequency self-alignment loop system.

$Delay(s) = e^{-\tau s}$ is a delay element. Due to a small time constant τ, in order to simplifying the calculation, the delay element can be equivalent as an inertial element $Delay(s) = \frac{1}{\tau s + 1}$ [10].

The receiver portion operates in the FPGA so that it needs 1ms to save digital data about the signal before each processing time, which means $\tau = 0.001s$ [11]. The delay element in this system is given below:

$$Delay(s) = \frac{1}{0.001s + 1} \tag{14}$$

Both external noise and internal noise have effect on the carrier frequency, which will influence performance of a pseudolite. External noise consists of random noise generated between up-conversion and down-conversion, external radio frequency interference and so on. Internal noise consists of random noise inside the FPGA, clock drift and so on[12]. The external noise effect is larger than the internal noise effect so that how to eliminate the external noise effect will be mainly focused on.

The four $RX(s)$ transfer functions are given below including second order PLL filter loop (15), second order PLL filter loop assisted with first order FLL filter loop (16), third order PLL filter loop (17), third order PLL filter loop assisted with second order FLL filter loop (18):

$$RX_{P2}(s) = \frac{66.5s^2 + 2221.2s}{s^2 + 66.5s + 2221.2} \tag{15}$$

$$RX_{P2F1}(s) = \frac{113.8s^2 + 2221.2s}{s^2 + 113.8s + 2221.2} \tag{16}$$

$$RX_{P3}(s) = \frac{55.1s^3 + 579.2s^2 + 12081.5s}{s^3 + 55.1s^2 + 579.2s + 12081.5} \tag{17}$$

$$RX_{P3F2}(s) = \frac{87.5s^3 + 1105.7s^2 + 12081.5s}{s^3 + 87.5s^2 + 1105.7s + 12081.5} \tag{18}$$

PID compensation will be chosen for this system (PI compensation actually) to compensate for the carrier frequency drift caused by the external noise because it can provide an integrating element and change the system into type 1 system, which steady-state error is zero for step input. Also, its parameters can be changed easily when real-time debugging in site.

Series compensation is not used in this system because it cannot provide an extra integrating element, which means that steady-state error always exists for step input. Feedforward compensation is not used in this system because external noise cannot be detected accuracy and we are not able to realize how external noise is generated. And bode compensation is also not used in this system because amplitude-frequency characteristic curve of the system does not cross 0dB line almost and crossover frequency does not exist.

So, the block diagram of this system is shown below:

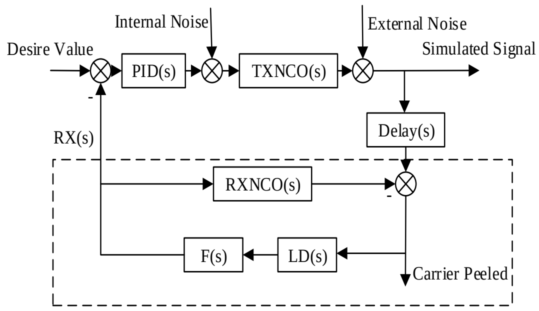

Fig. 11 carrier self-alignment loop block diagram with PID compensation

The block diagram in Figure 13 can be transformed into a form that its input is external noise.

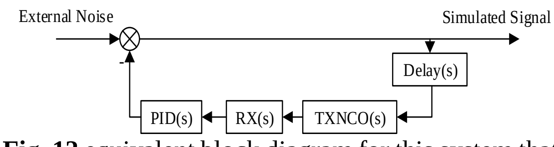

Fig. 12 equivalent block diagram for this system that input is external noise

According to Figure 14, related open-loop transfer function and closed-loop transfer function of the system can be obtained by Mason's gain formula:

$$PL_{col} = Delay(s)RX(s)PID(s)TXNCO(s) \quad (19)$$

$$PL_{ccl} = \frac{1}{1 + Delay(s)RX(s)PID(s)TXNCO(s)} \quad (20)$$

4.2 Analysis of carrier self-alignment system

The first priority of the analysis for this system is about stability. If closed-loop system is unstable, the pseudolite will malfunction sharply. Then, carrier frequency self-alignment ability will be considered.

At first, we set $PID(s) = K_P$ in order to analyze stability of the origin independent system.

In Figure 15, we can find that all those four systems are stable, no matter how K_P is, which also means the carrier frequency self-alignment closed-loop transceiver pseudolite can be realized. Phase margin and gain margin of the system can be obtained by open-loop bode diagram.

Now, we set $K_P = 1$. Closed-loop bode diagram of the system is shown in Figure 16. All of those four systems can suppress interference effect of low frequency signal input and cannot amplify the interference effect of high frequency signal input. Therefore, the carrier frequency self-alignment closed-loop is able to suppress effect of external noise and make the signal transmitted by the pseudolite more stable.

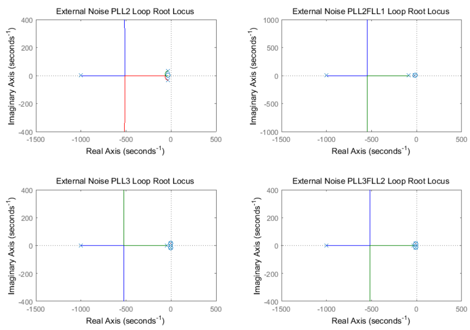

Fig. 13 system root locus for external noise input

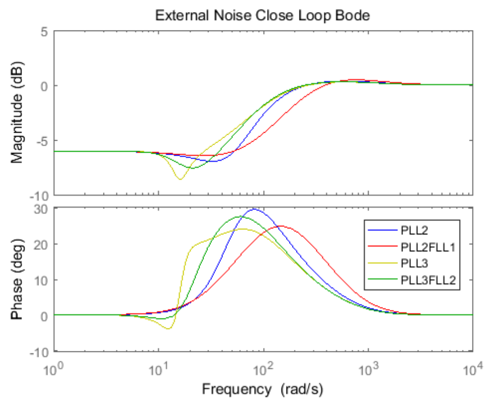

Fig. 14 system bode diagram for external noise input

In Figure 19, we can find that second order PLL assisted with first order FLL is better than the other when compared in transient-state performance. Thus, we will continue to use this filter structure in the following studies.

Table 1 phase margin and gain margin of carrier frequency self-alignment open-loop system

Order of PLL filer	Order of FLL filer	Phase Margin/°	Gain Margin
Second	None	123	∞
Second	First	144	∞
Third	None	136	∞
Third	Second	147	∞

In the proportion compensation, static-state error can be reduced by enlarging the value of K_P. Nonetheless, this method can only reduce static-state error not eliminate it. Therefore, integral compensation is necessary to eliminate the static-state error.

In some engineering projects, K_P and T_I can be set according to system timing response curve. However, it is intricate and inconvenient that debugging this closed-loop system is in the field so that this method will not be used in the carrier frequency self-alignment closed-loop system.

As we know, stability of the system will be reduced when integral compensation is brought in. In order to keep the system stable, equivalent root locus will be used to analyze the effect of integral time constant.

Equivalent root locus cluster ($K_p \le 1.804$) can be found by varying integral time constant for each proportion constant. Then, the critical value of K_P and T_I can be obtained from the equivalent root locus cluster. In order to simplify the related calculation, we just change the form of PID compensation compared with the default.

$$PI(s) = K_P(1 + \frac{T_I}{s}) \quad (21)$$

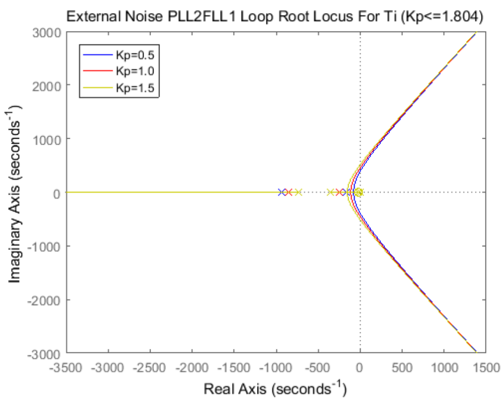

Fig. 15 equivalent root locus cluster for pi compensation of the system

In Figure 15 and Figure 17, if we set two constants $K_P \le 1.804$ and $T_I \le 113.04$, the system will be stable and non-overshooting because there are no conjugate poles in the system according to the related root locus.

Especially, non-overshooting response is needed for this system. If overshooting occurs, carrier frequency of the signal transmitted by the pseudolite may oscillate more severely due to oscillation superposition, which will make a universal receiver lose lock on the signal even the system is stable.

We set $K_P = 1.7$. Then, the whole system closed-loop bode diagram is shown in Figure 18.

According to Figure 18, this system has a significant effect on suppressing external noise interference effect of low frequency signal input. Also, it could not amplify any kind of external noise interference because the whole frequency specific curve is below the 0dB line almost.

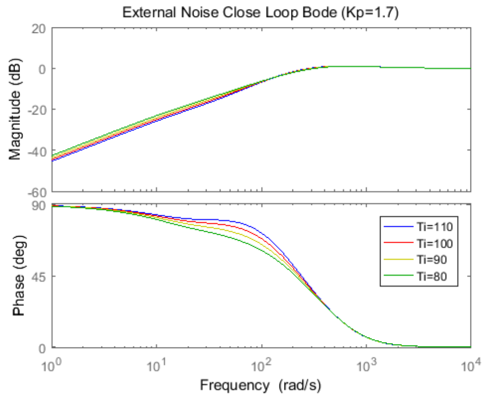

Fig. 16 bode diagram of different integral time constants in the system

5 Simulation Results

In this section, MATLAB Simulink is used to simulate the carrier frequency self-alignment carrier loop. Only two specific forms external noise, step and sine wave, are considered in the following simulation.

5.1 Carrier Frequency Self-Alignment Performance of Different Loop Filters Simulation

In the first section, only proportion compensation is used. We set input signals are unit step and $f = 20\pi$ Hz unit sine wave individually. Then we can find that performance of second order PLL loop filer assisted with first order FLL loop filer is better than the other when compared in rising time. According to Table 2, this loop filter is also better than the other at transient-state performance and suppression of low frequency sine interference. Thus, we choose this loop filter in the system.

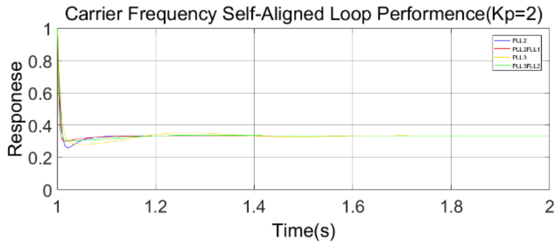

Fig. 17 the unit step response of different loop filters in the system

Table 2 performance specifications of different filters

Order of PLL filer	Order of FLL filer	Rising Time/ms	Overshoot
Second	None	7.303	11.479%
Second	First	5.001	5.228%
Third	None	10.681	6.660%
Third	Second	6.529	5.068%

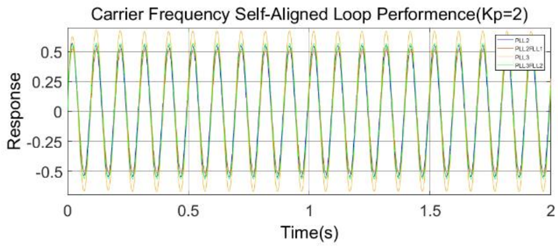

Fig. 18 the unit sine response of different loop filters in the system

5.2 PI Compensation

In the second section, PI compensation is brought in. We also set input signals are unit step and $f = 10\pi$ Hz unit sine wave individually. According to Figure 21 and Table 3, the static-state error does not exist with non-overshooting when integral compensation is brought in and the transient-state performance will enhance as T_I increases. According to Figure 22, low frequency sine interference is also suppressed by this system effectively.

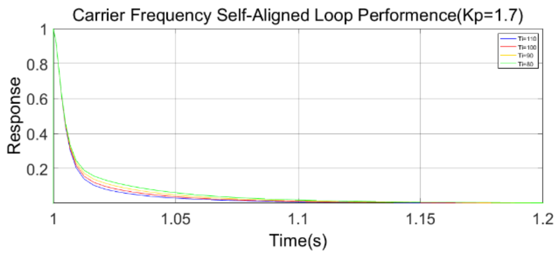

Fig. 19 performance of different integral time constants for the unit step signal input response

Table 3 performance of different integral time constant in pi compensation

Proportion Time Constant	Integral Time Constant	Rising Time/ms
1.700	110.0	15.142
1.700	100.0	18.482
1.700	90.0	22.808
1.700	80.0	28.524

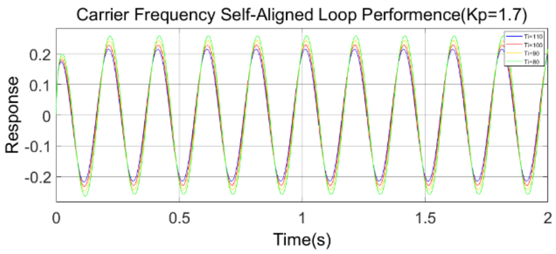

Fig. 20 performance of different integral time constants for the unit sine signal input response

Therefore, this carrier frequency self-alignment system is able to suppress to interference such as that in Figure 2.

6 Conclusions

In this paper, according to the analyses and simulation results in MATLAB Simulink, we can conclude that:

1. Carrier frequency self-alignment of the signal transmitted by a pseudolite is achievable via a closed-loop system.

2. The structure of the carrier frequency self-alignment closed-loop system is that a receiver loop, which is added into a general pseudolite, is used to feedback the signal transmitted by the pseudolite, which means the transceiver pseudolite can analyze signal transmitted by itself via the receiver loop and adjust the carrier frequency properly.

3. The second order PLL assisted with first order FLL in the receiver loop has better performance in suppressing external noise interference than the other filter structure listed in Table 2.

4. Using PI compensation in the carrier frequency self-alignment closed-loop system has a good ability to suppress external noise interference. It can reduce the effect of sine interference especially in a low frequency. The static-state error can be eliminated by the system when the external noise of the system is step interference.

References

1. Chen, Y., Zhan, X., and Tu, J. "A SVM Based GNSS Performance Assessment with Reliable Vulnerability Degree Model," *Journal of Aeronautics, Astronautics and Aviation* Vol. 50, No. 3, 2018, pp. 301-314.
2. Ma, C., Wang, J., and Chen, J. "Beidou compatible indoor positioning system architecture design and research on geometry of pseudolite," *Fourth International Conference on Ubiquitous Positioning, Indoor Navigation and Location Based Services*. 2017, pp. 176-181.
3. Lee, H. K., Wang, J., Rizos, C., and Tsujii, T. "Augmenting GPS by Ground-Based Pseudolite Signals For Airborne Surveying Applications," *Survey Review* Vol. 38, No. 296, 2005, pp. 88-99.
4. Lee, J. E., and Lee, S. "Indoor initial positioning using single clock pseudolite system," *International Conference on Information and Communication Technology Convergence*. 2010, pp. 575-578.
5. Liu, B., Zhan, X., and Liu, M. "GNSS/MEMS IMU ultra-tightly integrated navigation system based on dual-loop NCO control method and cascaded channel filters," *IET Radar, Sonar & Navigation* Vol. 12, No. 11, 2018, pp. 1241-1250.
6. Xie, G. *Principles of GPS and Receiver Design*. Beijing: Publishing House of Electronics Industry, 2017.
7. Kaplan, E. D., and Hegarty, C. J. *Understanding GPS: Principles And applicartions* London: ARTECH HOUSE, 2006.
8. Ding., J., Zhibin Luo, and Lin Zhao. "GNSS Carrier Tracking Loop With Loop Gain Control Factor," *Fifth International Conference on Instrumentation and Measurement, Computer, Communication and Control, IEEE*, 2015, pp. 1475-1480.
9. Tahir., M., Khurram., U. M., and Salman., A. "GNSS Carrier Tracking Loop : Stability Analysis and Some Improvements," *IEEE*, 2015, pp. 16-21.
10. W., J., and G., S. *Principles of Automation Control*. Beijing: Tsinghua University, 2009.
11. L., T. "The Design and FPGA Implementation of GPS Baseband Processor." Vol. Master, South China University of Technology, Guangzhou, China, 2011, pp. 18-25.
12. Rusu-Casandra, A., Marghescu, I., and Lohan, E. S. "Estimators of the indoor channel for GPS-based pseudolite signal," *International Symposium on Electronics and Telecommunications*. 2011, pp. 233-236.