Design and verification of GPS IF software analogue signal simulator

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Abstract

For the need of GPS intermediate-frequency (IF) analogue signal in various dynamics and disturbances, this paper has proposed a design to realize GPS IF signal simulator with software. Based on the given GPS satellite clock error and GPS signal transmission error, it analyzes their influence on signal acquisition and tracking as well as position calculation; deduces the mathematical model and analogue method of the ionospheric disturbance, the tropospheric disturbance and the multipath interference in the transmission of the navigation signal; designs the GPS IF analogue signal method based on software and chooses to use MATLAB software to realize GPS C/A Code IF signal simulator in L1 frequency. Through a software receiver which can successfully acquire and track the actual GPS signal, it verifies the correctness of the IF signal simulator; uses GPS IF signal simulator into GPS receiver development and gets arbitrary signal to noise ratio and the analogue GPS signals in various dynamics and disturbances for the developers of GPS receivers to investigate the influence of various errors on the receivers.

Keywords: satellite navigation, GPS, signal simulator, intermediate-frequency (IF) signal

1 Introduction

Global positioning system (GPS) is a global satellite navigation and positioning system with global and all-weather precise three-dimensional navigation and positioning as well as the timing service based on radio which is proposed by United States Department of Defense for the military purpose. It includes three parts: the satellite space constellation, the ground monitoring system and the receiver, which can be used for the land, air and space users [1, 2] and has been extensively used in the civilian fields such as navigation, communication and mapping [3-6]. The receiver is the only connector between the satellite navigation system and the users and the satellite navigation system can only realize timing service and positioning through user receiver [7, 8]. Therefore, it is of significant importance to research the realization of receiver on the applications and development of the satellite navigation.

With the development and the extensive applications of satellite navigation technology, the main space powers and alliances around the world have promoted their own satellite navigation systems one after another with GLONASS, GALILEO and COMPASS as the typical representatives [9-11]. Consequently, the new satellite navigation signals appear. The research and testing of various satellite navigation system receivers need the satellite analogue signal simulator to simulate the satellite navigation signal to provide input signal for the design, verification and testing of the receivers so as to examine the acquisition and tracking ability of the receivers [12]. Although the traditional analogue signal simulator based on hardware has good real-time performance, its design is not flexible enough and it must replace the relevant chip in the analogue simulator especially when producing new satellite navigation signal; therefore, it is not easy to upgrade at a low cost. On the contrary, the idea to use software radio can solve the above problem by uploading different application programs to realize the analogue of the satellite navigation signals in the hardware platform or PC.

This paper has made a detailed analysis of the several errors which have big influence on the GPS signal acquisition and tracking as well as the position calculation; provided their mathematical models and methods and designed a GPS analogue signal simulator method, based on which to realize GPS intermediate-frequency software analogue signal simulator by using MATLAB.

2 The main errors of GPS signal simulator

GPS software analogue simulator mainly analogues the various errors in the transmission path of GPS signals and

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the model of GPS software analogue simulator is indicated as Figure 1 [13]. The navigation signal sent by GPS satellite reaches the radio-frequency module of the user receiving unit after the ionospheric, tropospheric and multi-path delays and the radio-frequency module includes: the receiver antenna, the pre-amplification, the down-conversion and the intermediate-frequency processing unit, among which, the intermediate-frequency processing unit includes filtering and sampling and quantization. GPS analogue signal simulator mainly includes the following six errors: the ephemeris error, the satellite clock error, the pseudo-range error caused by ionospheric and tropospheric disturbances; the multi-path interference error and the noise error of the receivers.

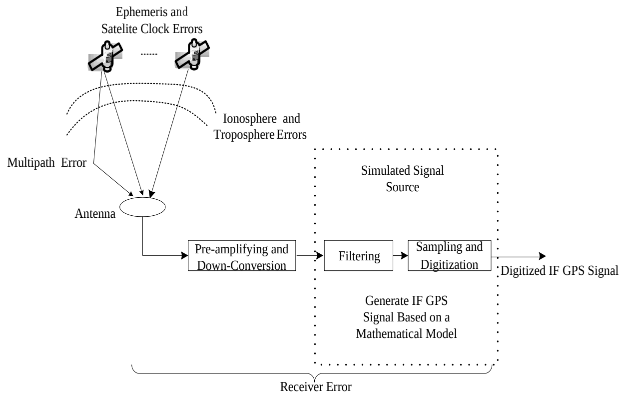

FIGURE 1 GPS software analogue signal simulator model

2.1 THE EPHEMERIS ERROR

Because the errors of the satellite position have little influence on the acquisition and tracking of the signals as well as the calculation of the user position, no analogue has made in the GPS analogue signal simulator in this software.

2.2 THE SATELLITE CLOCK ERROR

Every satellite has an atomic clock to preserve the accurate time and the degree of accuracy is 10-13. It is controlled by GPS control section and the main errors of this part comes from SA strategy. Since SA strategy is closed, the rest errors are mainly caused by the slow changes of clock signal [14]. The rest part has few errors and it has little influence on signal tracking and acquisition; however, it has much effect on the position calculation. Such errors can be simulated by downloading the telegraph text in the GPS analogue simulator in this software.

2.3 THE PSEUDO-RANGE ERRORS CAUSED BY IONOSPHERIC AND TROPOSPHERIC DISTURBANCES

When the GPS signal crosses through the upper atmosphere, the free electron in the atmosphere affects the speed of the GPS signal transmission and causes the TOA (time of arrival) error of the receiver [15-17]. This kind of error has different influence on the code and the carrier wave. It causes the delay of the code phase, but it makes the carrier wave phase move forward and the affecting range is among 5-150 meters.

The pseudo-range errors formed in the troposphere mainly come from the scattering and refraction of GPS signals made by the troposphere [17]. Just as the ionospheric disturbance, troposphere will also affect the transmission speed of GPS signal and it will have the same delay to the code and the carrier wave. In the GPS analogue simulator in this software, the ionospheric and tropospheric error model is adopted to calculate their errors.

2.4 THE MULTI-PATH INTERFERENCE ERROR

The main reason for the multi-path interference errors is the errors caused by the reflected signals entering in the receiver antenna and its size is subject to the influence of the reflective objects, the antenna gain and the correlators in the receiver [18]. The multi-path interference affects the precision measurement of the receiver and it has influence on the code and the carrier wave, but it has played more effect on the code than on the carrier wave. Its maximum impact on the code can reach half a code, but it won't have influence on no more than 1/4 wave length of the carrier wave. To every receiver, the multi-path interference is different. The multi-path interference error analogue in this GPS analogue simulator is realized through the below mathematical model.

2.5 THE NOISE ERROR OF RECEIVER

The noise errors of the receiver mainly are divided into the following two kinds: one is the error related to the processing methods of the receiver such as sampling and quantization errors, the tracking loop and the hardware precision losses. The other is the accuracy limit of the component parts such as the accuracy of the crystal oscillator and the irrelevant system noise [19]. In this GPS software analogue signal simulator, simulate the noise interference with Gaussian white noise; realize the signal filter via the band-pass filter with a bandwidth of 3MHz and quantize the data into 4 bits.

3 The mathematical model and analoguey methods of the error

3.1 THE GENERATION OF THE NAVIGATION SIGNAL

Without considering *P* code, the signals in the L_1 frequency sent by the common GPS satellite can be expressed as [13]

$$S_{L1i} = \sqrt{2P_i} D_i(t_{tr}) C_i(t_{tr}) \cos(\omega_{L1} t_{tr} + \varphi_0). \quad (1)$$

In the Equation, S_{L1i} is the signal sent by the *i-th* satellite in the L_1 frequency. P_i is the signal energy of the coarse/acquisition code; $D_{i(tr)}$ is the navigation data. $C_{i(tr)}$ is the coarse/acquisition code; ω_{L1} is the carrier frequency of L_1. *tr* is the signal transmission time and φ_0 is the initial phase of GPS signal. Assuming that is the satellite clock error, the coarse/acquisition code signal in L_1 frequency can be expressed as

$$S_{L1i} = \sqrt{2P_i} D_i(t_{tr} + \delta t_{SV}) C_i(t_{tr} + \delta t_{SV}) \cdot \cos[\omega_{L1}(t_{tr} + \delta t_{SV}) + \varphi_0]. \quad (2)$$

Considering the navigation signal transmission delay, the ionospheric and tropospheric disturbances, the coarse/acquisition code signal in the L_1 frequency can be expressed as

$$S_{L1i} = \sqrt{2P_i} D_i(t_{tr} - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV}) \cdot C_i(t_{tr} - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV}) \cdot \cos[\omega_{L1}(t_{tr} - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV}) + \varphi_0] \quad (3)$$

T_p is the transmission delay; δt_{iono} is the ionospheric delay and δt_{iropo} is the tropospheric delay. The signal can be expressed as follows with the multi-path interference and noise.

$$S_{L1i} = \sqrt{2P_i} D_i(t_{tr} - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV}) \cdot C_i(t_{tr} - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV}) \cdot \cos[\omega_{L1}(t_{tr} - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV}) + \varphi_0] + MP_i + Noise. \quad (4)$$

3.2 THE GENERATION OF MULTI-PATH SIGNAL

In order to get multi-path signals, a section of spread spectrum code-sequence needs to be cached. The experiment shows that the multi-path signal with a time delay bigger than 1.5-fold spread code chip width has little influence on the receiver; therefore, the coarse/acquisition code in this design stores the past 2 code chips. Besides, the multi-path signal will add the hopping of a carrier wave phase in the reflection points in its transmission points. Apart from the influence of the additional transmission time delay, the carrier wave phase of the multi-path interference signal is also affected by this phase hopping, the formula of which is [18]

$$MP_i = \alpha\sqrt{2P_i} D_i(t_{tr} - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV} - \delta t_{MP}) \cdot C_i(t_{tr} - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV} - \delta t_{MP}) \cdot \cos[\omega_{L1}(t_{tr} - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV} - \delta t_{MP}) + \varphi_{MP}]. \quad (5)$$

In this Equation, α is the multi-path fading factor; δt_{MP} is the multi-path delay and φ_{MP} is the phase mutation caused by the multi-path interference reflection points.

3.3 THE GENERATION OF NOISE INTERFERENCE SIGNAL

The interference includes: noise interference and single-carrier wave interference and the formula of single-carrier wave interference is [20]

$$S_{CW} = \sqrt{2P_{CW}} \sin(2 * \pi * f_{CW} * t) \quad (6)$$

The amplitude and frequency of single-carrier wave interference signal can be set through parameters and it means closing single-carrier wave interference when P_{CW} is set 0.

Noise interference is mainly the white noise signal producing Gaussian distribution and it can be produced from the approximate sum of several random variables which are distributed independently. The mean square error of Gaussian noise σ_N can be set randomly and the integrated noise items are

$$Niose = S_{CW} + N_o \quad (7)$$

3.4 THE GENERATION OF INTERMEDIATE-FREQUENCY NAVIGATION SIGNAL

The local down-conversion signal can be expressed as [21]

$$LO_1 = 2\cos[\omega_{Lo}(t_r + \delta t_r)]3 \quad (8)$$

Among them, ω_{L0} is the frequency of local carrier wave; t_r is the mixing time; δt_r is the local clock difference and the intermediate-frequency signal S_{IFi} can be expressed as

$$S_{IFi} = S_{L1i} \cdot LO_1 \quad (9)$$

In the GPS analogue signal simulator of this software, filter the radio-frequency components without considering the influence of the local clock difference δt_r and get

$$S_{IFi} = \sqrt{2P_i} D_i(t - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV}) \cdot C_i(t - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV}) \cdot \cos[\omega_{L1}(t - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV}) + \varphi_0 - \omega_{LO}(t + \delta t_r)]$$

$$= \sqrt{2P_i} D_i(t - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV}) \cdot C_i(t - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV}) \cdot \cos[(\omega_{IF} t - \omega_{L1}(T_p + \delta t_{iono} + \delta t_{iropo} - \delta t_{SV}) + \varphi_0]. \quad (10)$$

$$MP_i = \alpha\sqrt{2P_i}D_i(t - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV} - \delta t_{MP})$$
$$C_i(t - T_p - \delta t_{iono} - \delta t_{iropo} + \delta t_{SV} - \delta t_{MP}) \quad (11)$$
$$\cos[\omega_{IF}t - \omega_{L1}(T_p + \delta t_{iono} + \delta t_{iropo} - \delta t_{SV} + \delta t_{MP}) +$$
$$\varphi_{MP}].$$

Get the intermediate-frequency signal and multi-path interference error from the above two formulas and get the compound signal of several satellites by adding the signals and noises of N satellites.

$$S_{IF} = \sum_{i=1}^{N}(S_{IFi} + MP_i) + Noise\,. \quad (12)$$

According to Equation (10), get GPS analogue signal simulator structure, as indicated in Figure 2.

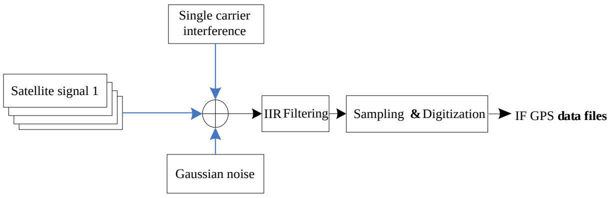

FIGURE 2 GPS analogue signal simulator structure

Every satellite signal is generated by Equation (1) and its structure diagram is as indicated in Figure 3. Realize the satellite clock error analogue by downloading user teletext; get the errors caused in the ionospheric and tropospheric pseudo-range by establishing ionosphere and troposphere models; simulate noise source with Gaussian white noise; generate the navigation signal with an intermediate frequency of 8.184 MHz; quantize into 4-bit GPS analogue data and store in the computer hard disk drive. Among them, the ranges of Gaussian noise and single-carrier wave can be adjusted and IIR filter is to simulate radio frequency front-end path filter.

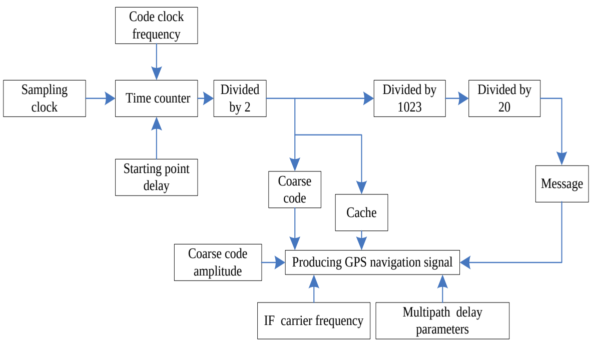

FIGURE 3. The generation of single satellite navigation signal

The time counting in Figure 3 is completed by frequency control. “Initial delay” is to simulate the different signal delays when different satellites reach the ground. The driving clock of CA code is generated from the time counting. The time counting generates 2-fold code clock frequency and the driving code is generated after 2 fractional frequencies. “Cache” is to simulate multi-path signals and the range of the multi-path signals and the phase jumping volume can be adjusted.

4 The Verification of analogue signal simulator

4.1 THE GENERATION OF INTERMEDIATE-FREQUENCY ANALOGUE GPS SIGNAL

According to the above GPS analogue signal simulator structure, choose MALTAB software programming to realize GPS intermediate-frequency software analogue signal simulator and generate the distribution of intermediate-frequency signals and signals, as indicated in Figure 4. It can be seen from Figure 4 that the signal values are the integers from -8 to +7 and they approximately follow Gaussian distribution.

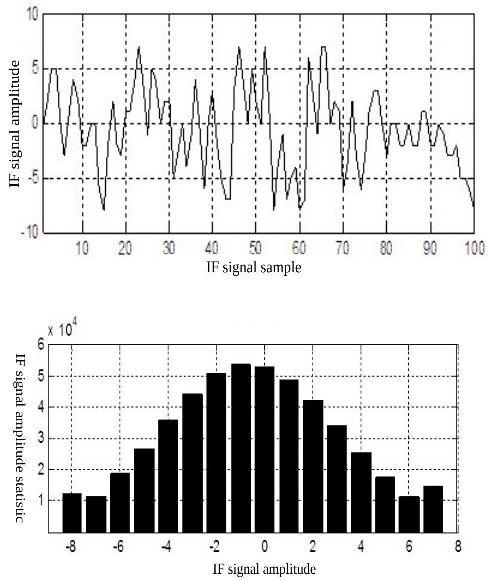

FIGURE 4 The analogue intermediate-frequency signal

4.2 THE VERIFICATION OF INTERMEDIATE-FREQUENCY ANALOGUE GPS SIGNAL

In order to verify the generated intermediate-frequency analogue GPS data, firstly use a software receiver to acquire and track the actual real-time signals and get the satisfactory results. Then, use this software receiver to conduct acquisition, tracking and data demodulation of the data generated by the analogue signal simulator. In this software, acquire the signals with FFT; track, demodulate and de-spread the generated signals by combining second FLL and second PLL; verify the analogue such as multi-path interference, frequency hopping and frequency ramp and the results are indicated as Figure 5, Figure 6 and Figure 7.

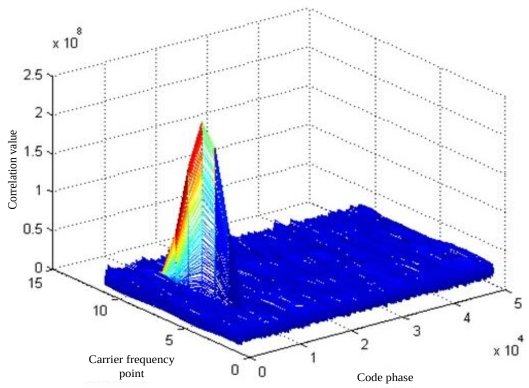

FIGURE 5 FFT acquisition result

Figure 5 demonstrates the acquisition result of the satellite in the generated analogue GPS intermediate-frequency signal and it can be seen that the analogue intermediate-frequency GPS signal simulator can realize accurate acquisition.

Figure 6 displays the tracking results of FLL and PLL. In FLL output, the normalization errors of some sampling points are different, indicating that there is a big frequency hopping here and verifying that the analogue GPS signal simulator is correct in the frequency hopping analogue. From the tracking error output of PLL, it can be seen that there is a stable phase difference in PLL output caused by the frequency ramp, which verifies the correctness of the frequency ramp analogue.

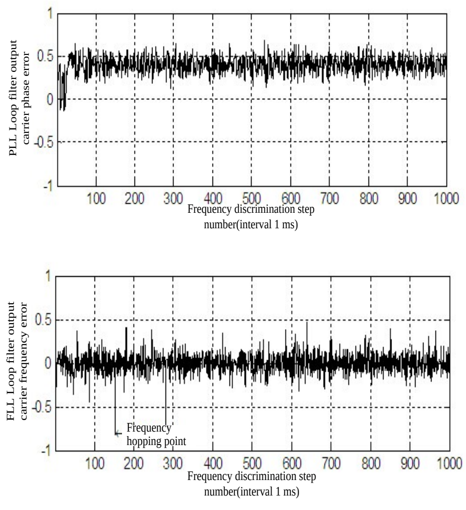

FIGURE 6 The analogue signal simulator tracking result

Figure 7 has shown the data demodulation result of the analogue signal simulator and it can be seen that the generated analogue GPS intermediate-frequency data can smoothly demodulate the data so as to conduct smooth bit synchronization, frame synchronization and navigation calculation and verify the correctness of the entire GPS analogue signal simulator design.

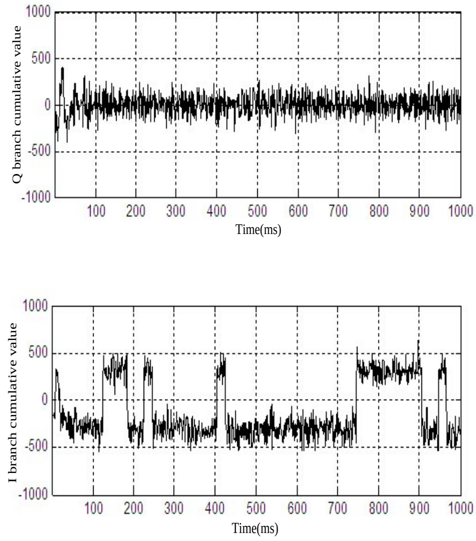

FIGURE 7 The data demodulation result

5 Conclusion

By analyzing the main GPS signal error simulator, this paper explores the errors which have a big impact on the signal acquisition and tracking as well as position calculation in GPS analogue simulator; provides their mathematical models and analogue methods; proposes a GPS analogue signal simulator system design plan based on software implementation according to these mathematical models and chooses MATLAB software to realize GPS C/A code intermediate-frequency analogue signal simulator. An accurate GPS software receiver can realize the accurate acquisition, tracking and demodulation of the analogue signal and proves that the analogue simulator design plan is correct. This analogue signal simulator can get arbitrary signal-to-noise ratio and GPS data in various dynamic conditions only with simple parameter setting and store the data in the computer to be directly invoked by the receiver so as to be used to test the performance of various receivers. Compared with the expensive hardware GPS signal simulator, it can only reduce the design costs and improve the product competitiveness, but it can also be used to develop GLONASS and COMPASS signal simulator through rewriting, which can fully demonstrate its superiority.

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