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Analysis and Simulation on the Key Technology of GPS Simulator Based on Software Platform

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Abstract. Motivated by the requirement of providing real-time and realistic signal for the GPS receiver testing, a variety of software or hardware platform based GPS simulators are devised. In actual environment the GPS signals that the GPS receiver received always contain uncertain propagation delay and noise or jamming. So it's difficult to test the performance of a receiver especially for high dynamic environment. A GPS simulator could provide realistic scenarios that a receiver may encounter just by testing a receiver in laboratory. This makes it very convenient for a receiver testing benefit from the flexibility of the simulator with radio and digital signal. This paper focus on the key technologies of software based GPS simulator including the main simulation errors such as ionosphere delay, troposphere delay, multipath model and so on. The structure of the software simulator is given and the DDS based NCO is proposed to calculate the Doppler frequency and signal delay with detailed step. Finally results are presented proving the simulated signal.

Keywords: GPS, simulator, matlab, multipath.

1. Introduction

GPS receivers are now popularly used in every-day life. Variety receivers provide different precision for position, navigation and timing. The performance of a receiver is assessed by its ability to precisely measure the pseudorange and carrier phase, and its sensitivity and high dynamic ability are also concerned. A GPS receiver for civil use is often tested with the real outdoor satellite signal since its low-grade requirement. But GPS receivers for GPS guided weapons are not easy to be tested of its precision and dynamic ability, even the experiment is very expensive and dangerous. For real world GPS signal, the scenario will not repeat for compare. The GPS signal at the receiver antenna is susceptible to interference or jamming, and GPS observations are corrupted with much error sources [1, 2, 3].

For these reasons GPS simulator draws more attention during the past decade. The GPS simulator is a type of widely used device providing realistic signal for GPS receiver and system testing. Some simple single-channel simulators are developed for CA code acquisition and tracking testing. Some multi-channel simulators are also developed providing the ability of position, timing, sensitivity and high dynamic testing and so on. GPS satellite simulator provides a convenient experiment platform for GPS receiver and GPS system by simulating realistic signal [4, 5, 6].

This paper aims to analyze the framework of the software-based simulator and its key technologies especially the error sources. The core procedure for a simulator that the NCO based signal generation is proposed. The paper is organized as follows.

First the analytic expression GPS signal model is presented with the satellite signal propagation concern from the satellite to the receiver. In the second section the framework and key technologies is well analyzed

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for a software-based simulator. And then the key procedure of signal generation based on NCO technology is presented in detailed steps. Main propagation error sources are given including ionosphere delay, troposphere delay, multipath error. Finally, the simulated digital signal is tested. And for well-known reason only the CA signal is concerned in this paper.

2. GPS Signal Model for Simulator

The GPS signal transmitted from the satellite will take about 70ms to arrive the receiver. In the space propagation it will involves ionosphere delay and troposphere delay effects to the signal. The signal is also linked with noise and multipath signals. In the receiver the radio frequency signal received at the antenna is often first down-converted to intermediate frequency and sampled for digital signal processing. For convenient the software based simulator only simulate IF digital signal, so the IF signal model should be developed.

The GPS L1 frequency signal transmitted from one satellite with particular C/A code i can be represented as [7, 8]

$$S_i = \sqrt{2P_{ti}} D_i(t_{tr}) CA_i(t_{tr}) \cos(w_{L1} t_{tr} + \varphi_i) \tag{1}$$

where, S_i is the GPS L1 signal transmitted from satellite i, P_{ti} is the transmitted signal power, D_i is the navigation data, CA_i is the particular C/A code of satellite i, w_{L1} is the L1 carrier frequency equal to $2\pi * 1575.42$ MHz, t_{tr} is the signal transmit time based on the satellite clock, φ_i is the initial phase of the signal at time t_{tr}.

In common the satellite time is not consistent with GPS system time, in other words it has a satellite clock bias. With the presence of the satellite clock error, the transmitted signal can be described as

$$\begin{aligned} S_i = {} & \sqrt{2P_{ti}} D_i(t_{tr} + \delta t_{svi}) CA_i(t_{tr} + \delta t_{svi}) \\ & \cos[w_{L1}(t_{tr} + \delta t_{svi}) + \varphi_i] \end{aligned} \tag{2}$$

where, the δt_{svi} is the clock error of satellite i.

Then the transmitted satellite signal will reach the antenna through space propagation that involves time delay and ionosphere delay and troposphere delay effects to the signal. The expression can be write as

$$\begin{aligned} S_i = {} & \sqrt{2P_i} D_i(t_{tr} + \delta t_{svi} + t_{sp} + \delta t_{iono} + \delta t_{tropo}) \\ & CA_i(t_{tr} + \delta t_{svi} + t_{sp} + \delta t_{iono} + \delta t_{tropo}) \\ & \cos[w_i(t_{tr} + \delta t_{svi} + t_{sp} + \delta t_{iono} + \delta t_{tropo}) + \varphi_i] \end{aligned} \tag{3}$$

where, P_i is the received power attenuated, t_{sp} is the space propagation time which is also the range producted with velocity of light, δt_{iono} is the ionosphere delay, δt_{iono} is the troposphere delay, w_i is usually no longer the L1 but the sum of L1 frequency and the doppler frequency induced by the relatively movement between the satellite and the receiver. Certainly the signal is always added with noise, interference and multipath but omitted by equation (3).

At the receiver front-end after the antenna the signal in equation (3) is down-converted to the desired intermediate frequency (IF). The front-end generates a cosine signal for the RF mixing with a nominal L1 frequency of 1575.42MHz.

$$L(t) = 2\cos(w_{L1} t) \tag{4}$$

And the mixing means the product as follows

$$Y_i = S_i * L(t) \tag{5}$$

Through some simplify and filtering the high frequency, we obtain the IF frequency signal

$$\begin{aligned} S_{iIF} = \sqrt{2P_i} D_i (t_{tr} + \delta t_{svi} + t_{sp} + \delta t_{iono} + \delta t_{tropo}) \\ CA_i (t_{tr} + \delta t_{svi} + t_{sp} + \delta t_{iono} + \delta t_{tropo}) \\ \cos[w_{iIF} (t_{tr} + \delta t_{svi} + t_{sp} + \delta t_{iono} + \delta t_{tropo}) + \varphi_i] \end{aligned} \tag{6}$$

where the w_{iIF} means the nominal IF frequency summed with the doppler frequency of RF propagation. Other parameters of equation (3) will not change.

Then the intermediate frequency analog signal of equation (6) is always sampled with A/D device as IF frequency digital signal for baseband signal processing in the receiver.

Equation (6) is the analytical model of a satellite signal and it is the basis for the development of a software based simulator. The power P_i, the navigation data D_i, C/A code CA_i, IF carrier with frequency of w_{iIF} should be simulated for signal modulation. The time elements of the equation are also the key issues.

The noise and multipath signals should be simulated together with equation (6). Multipath signal is always a time delayed and amplitude fading copy of the direct signal and could be expressed as

$$S_{iMP}^k = \alpha_{MP}^k S_{iIF} (t + \delta t_{MP}^k) \tag{7}$$

Where, α_{MP}^k is the power attenuation factor, δt_{MP} is additional propagation math time of the multipath signal relatively to the direct signal in equation (6), thus it will take δt_{MP}^k time more than the direct signal, and the integer k denotes the k-th multipath signal.

The simulator aims to simulate all signals at the antenna. So compositing signals of all satellites in view and take noise and interference into account the final signals are expressed as

$$S = \sum_{i=1}^{N} (S_{iIF} + \sum_{k=1}^{M} S_{iMP}^k) + noise \tag{8}$$

where N is the number of satellites in view, M is the number of multipath.

3. Software GPS Simulator Framework and Key Technologies Based on Matlab Platform

The GPS signal mode has been established as shown in equation (8). The task of the simulator is to form all the parameters in equation (6) and (8) and these are also the key technologies of a simulator and will be analyzed one by one.

The power P_i affects the C/N0 measurement of a receiver. It should be concerned together with the variance of noise.

The navigation data D_i with 50 bps should be consistent with the GPS ICD document. The navigation data is coded with satellite ephemeris which could be downloaded from the GNSS website.

The particular C/A code CA_i with nominal 1.023 MHz frequency is generated from the product of two 1023-bit PRN sequences.

A cosine typed IF carrier with frequency of w_{iIF} is much simple to produce using MATLAB. But more attention should be pay to the time variant frequency w_{iIF} that is depended on the movement of both the satellites and receiver. So the trajectory of satellites and receiver should be simulated in high precision because it will also affect the pseudorange which is the time parameters t_{sp} in equations.

In equation (6) the δ time parameters are always the error sources of a receiver. They are satellite clock bias, ionosphere error and troposphere error that could be simulated by ephemeris parameters or by typical model which the receiver adopted.

Through the elements analysis the framework of a simulator is formed in Fig. 1.

This simulator structure in Fig. 1 is completely based on the signal simulation model as represented in Equation (6) and equation (8).

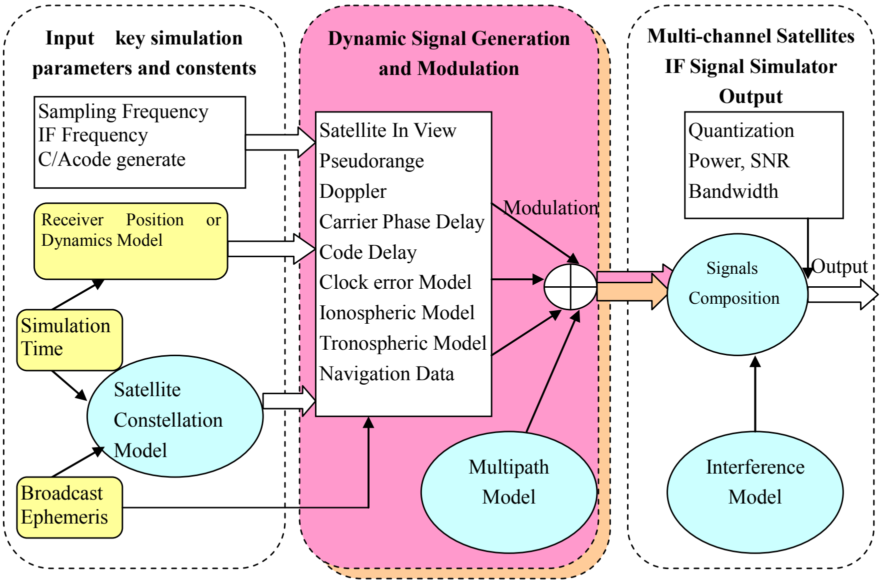

Fig. 1: Framework of a GPS simulator.

To start the simulation, the ephemeris and the simulation time and the receiver trajectory are the three basic input conditions. The receiver trajectory is simulated as user desired which is also called the simulation scenario. And the satellite's positions are computed based upon the simulation time and the satellite ephemeris.

Then, the signal propagation time in other words the range, Doppler, and errors are calculated to generate the required carrier and code components. How to generate precise signal components are the core technologies of a simulator and will be presented in next section.

The IF GPS signal for a single satellite is the product of these components. Then, the composite IF signal is computed by the summation of noise and the signals of all satellites in view. And the overall signal is output and will be saved as a data file to the disc for receiver testing.

4. Dynamic Signal Generation for Multi-Channel Simulator

It's obvious in Fig. 2 that key technology of a simulator is the second step that the calculation of signal generation with precise doppler frequency and delays. DDS (Direct Digital Frequency Synthesizer) based NCO technology [8] is adopted for the computation of IF signal generation. A pseudorange-change based method is proposed here to calculate the Doppler and signal phase delay simultaneously. Main computation procedure will be presented in detail below.

4.1 . DDS Bsed NCO computation of IF signal generation

First, confirm all the parameters in Fig. 3 including the receiver positions and satellites in view.

Given the initial simulation time t_0 of GPS system time，the receiver will receive the signal which is transmitted at time before t_0 of τ_0 second, thus the pusudorange between the receiver and the satellite is known that $\rho_0 = c \cdot \tau_0$, in which c is the speed of light. While at GPS system time $t_0 - \tau_0$, the GPS signal is determined from equation (6), ignoring all the delta time elements is equation (6), we get the transmitted signal

$$S_{t_0} = \sqrt{2P_i} D_i(t_0 - \tau_0) CA_i(t_0 - \tau_0) \cos[w_{L_1}(t_0 - \tau_0) + \varphi_i] \tag{9}$$

When t_0 is integer seconds of GPS system time, φ_i is zero, then

$$S_{t_0} = \sqrt{2P_i} D_i(t_0 - \tau_0) CA_i(-\tau_0) \cos[-w_{L1}\tau_0] \tag{10}$$

In which, t_0 is not omitted in navigation element because the minimal navigation data period is above 6 seconds.

Suppose in short sample time period Δt_s at the receiver, the radial velocity between the satellite and the receiver is constant, so at time $t_1 = t_0 + \Delta t_s$ if the pseudorange is ρ_1, and $\Delta\rho$ is $\rho_1 - \rho_0$. If $\Delta\rho$ equal zero, it means the Doppler frequency is zero and the received signal frequency should be nominal frequency L1. So doppler frequency is also determined by the velocity of $\frac{\Delta\rho}{\Delta t_s}$, and $\Delta\rho$ shows the doppler carrier phase increment. So the signal at time t_1 is

$$\begin{gathered} S_{t_1} = \sqrt{2P_i} D_i(t_0 - \tau_0 + \frac{\Delta\rho}{c}) CA_i(-\tau_0 + \frac{\Delta\rho}{c}) \\ \cos[w_{L1}(-\tau_0 + \Delta t_s + \frac{\Delta\rho}{c})] \end{gathered} \tag{11}$$

Total carrier phase increment is

$$w_{L1}\Delta t_s + w_{L1}\frac{\Delta\rho}{c} \tag{12}$$

Where, $w_{L1}\Delta t_s$ denote the nominal carrier phase increment, $w_{L1}\frac{\Delta\rho}{c}$ denotes the doppler carrier phase increment.

Using IF signal model, equation (12) is converted to

$$w_{IF}\Delta t_s + w_{L1}\frac{\Delta\rho}{c} \tag{13}$$

Using NCO theory, $-w_{L1}\tau_0$ is initial carrier phase in equation (10), and suppose use 36-length carrier NCO, the initial register is

$$N(0) = \frac{\mathrm{mod}(-w_{L1}\tau_0, 2\pi)}{2\pi} 2^{36} \tag{14}$$

Then the final IF frequency based carrier NCO frequency word is

$$NCO\_WORD = \frac{w_{IF} + w_{L1}\frac{\Delta\rho}{c\Delta t_s}}{2\pi} \times \frac{2^{36}}{f_s} \tag{15}$$

Where f_s is the IF sampling frequency.

Equation (14) and (15) are the basic NCO based carrier signal generate model.

C/A code could be processed like the carrier。

Navigation data is modulated at the beginning and end of a 1023-chip C/A code.

Thus all the three modulation parts are determined.

4.2 Compensation of propagetion errors model

In equation (9), all the delta time elements are omitted. They could be regard as the time errors based on known model including the satellite clock error model, ionosphere error model, troposphere error model, multipath model.

(1) Satellite Clock Error Model

In the ephemeris four parameters, $toc, a_{f0}, a_{f1}, a_{f2}$ are provided to correct the satellite clock bias

$$\delta t_{sv} = a_{f0} + a_{f1}(t - toc) + a_{f2}(t - toc)^2 \tag{16}$$

(2) Ionosphere Error Model

In satellite ephemeris 8 inonsphere parameters are issued $\alpha_i, \beta_i (i = 0,1,2,3)$ to calculate the ionosphere error. Using Klobuchar model, ionosphere error is [9]

$$\delta t_{iono} = \begin{cases} F \times \left[5\times10^{-9} + \sum_{i=0}^{3} \alpha_i \Phi_m^i \times (1 - \frac{x^2}{2} + \frac{x^4}{24}) \right] & |x| < 1.57 \\ F \times 5\times10^{-9} & |x| > 1.57 \end{cases} \quad (17)$$

In which $x = \frac{2\pi(t-50400)}{\sum_{i=0}^{3} \beta_i \Phi_m^i}$, Φ_m is specific geomagnetism latitude, and F is the incline factor

$$F = 1.0 + 16.0 \times (0.53 - \theta)^3 \quad (18)$$

(3)Troposphere Error Model

Hopfield model is commonly used for troposphere error model

$$\begin{cases} \Delta\rho'_{trop} = \frac{K'_d}{\sin(E^2 + 6.25)^{1/2}} + \frac{K'_W}{\sin(E^2 + 2.25)^{1/2}} \\ K'_d = 1.552\times10^{-5} \frac{p_0}{T_k}(h_d - h_u) \\ K'_W = 7.46512\times10^{-2} \frac{e}{T_k^2}(h_w - h_u) \\ h_d = 40136 + 148.72(T_k - 273.16) \\ h_W = 11000 \end{cases} \quad (19)$$

For details please refer to the reference [2, 9].

(4)Multipath Error Mode [2]

There are some simple static or dynamic echo models for multipath [2]. The multipath could be generated by the delay of direct signal.

5. Simulation and Results

The procedure of generate software IF GPS simulator is conduct using MATLAB. Here the IF frequency is 4MHz, and sampling frequency is 16MHz. Conform the input conditions including the ephemeris and simulation time and the user position specific IF GPS signals are generated. Bellow we presented some verification figures including the satellites in view at initial simulation time at Fig. 2. Fig. 3 is the temporal wave of one signal and Fig. 4 is the spectrum. For farther testing the IF data should be introduced to a software receiver.

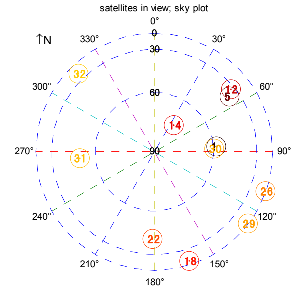

Fig. 2: Satellites in view .

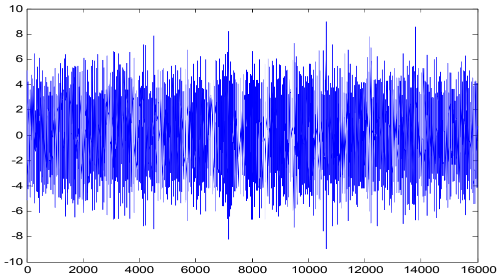

Fig. 3: Temporal wave of one satellite signal.

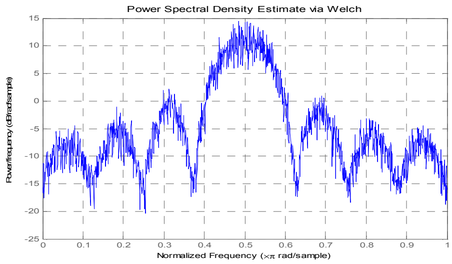

Fig.4: Frequency spectrum of the signal.

6. Conclusion

In this paper we have presented and discussed the detailed signal model and structure of a software based GPS simulator. The test results presented in this paper have demonstrated the utility of the MATLAB software based IF GPS signal simulator. The simulator could be used for GPS signal analysis and GPS software receiver test and technology development. This simulator has the following advantages over previous analog GPS simulators.

- Easy of all levels of satellite signal generator control stage.
- Flexibility of input conditions modify
- High fidelity of methods development.
- Digital data storage for exact reconstruction and playback of signal simulation profiles for testing

7. Acknowledgment

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