Design and Applications of a Generalized Software-Based GNSS IF Signal Generator

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Abstract

In this paper, design and applications of a generalized, versatile and customizable IF signal generator that can model the modernized GPS and Galileo signal is given. It generates IF sampled data that can be directly used by a software receiver. Entire constellation of satellites which is independent of satellite-user geometry is easily determined using a real or simulated ephemeris data. Since the IF center frequency, sampling frequency and quantization bit number are user location dependent parameters, their effects are also considered in IF signal generator. The generalized IF signal generator will be very well suited for the development phase of a software receiver due to its versatility. The full access to the sampling frequency, front-end filter definition and ADC parameters also offers a great opportunity for cost-effective analysis of tracking loops and error mitigation techniques at the receiver level. Interference sources can be easily added to the generator to simulate specific environments. This software IF signal generator can also be used to feed a multi-frequency multi-system software receiver for the prototyping of a combined GPS/Galileo receiver. The test result using the generated signals and a real software receiver shows the effectiveness of the implemented IF signal generator.

Keywords: GNSS, IF Signal Generator, L2C, BOC(1,1)

1. Introduction

The recent development of software based Global Navigation Satellite Systems (GNSS) receivers has brought a new perspective to receiver design. The first requirement to use them is to have sampled data at an Intermediate Frequency (IF). These sampled data can be provided through two different ways; hardware and software. First, a hardware based RF front-end that could sample data coming from either the real satellites or a simulator. Real signals might not be available when GNSS is under development as in the case of GPS (Global Positioning System) L2C and Galileo. Hardware GNSS simulators were used to fill this gap, and they are now widely used. However, they are very expensive and may not generate special signals of interest and consequently might not be always suitable for specialized research due to the lack of flexibility. Secondly, sampled data can be generated by a software called IF signal generator. Such a tool includes GNSS signal generation program as well as hardware simulation program for filtering and sampling, therefore generated IF signals can be directly fed into a software receiver. There are already some researches about the GNSS IF signal generator [1], but Galileo signal generation may not be complete because the Galileo ICD (Interface Control Document) is released recently.

The first part of this paper will summarize the development of a GPS L1 IF signal generator. The second part will focus on the new GNSS signals generations such as GPS L2C and Galileo BOC (Binary Offset Carrier). Finally, the third part will focus on the verification of generated signals through its power spectral density and tracking availability in the software receiver.

2. A Proto GPS L1 Signal Generator

The IF GPS Signal Generator structure is given in Figure 1. The navigation data in this structure are loaded from the file, which is obtained by real receivers or generated by GPS L1 simulator (STR4500). It allows the simulation of a real GPS constellation at a given time. The ephemeris data take account relativistic effects to do more realistic simulation. The satellites below a specified elevation mask angle are disregarded. Once the satellites in view are selected and their positions computed, the signals coming from each satellite are modeled. The model used in the GPS IF signal generator is given in Eq. (1).

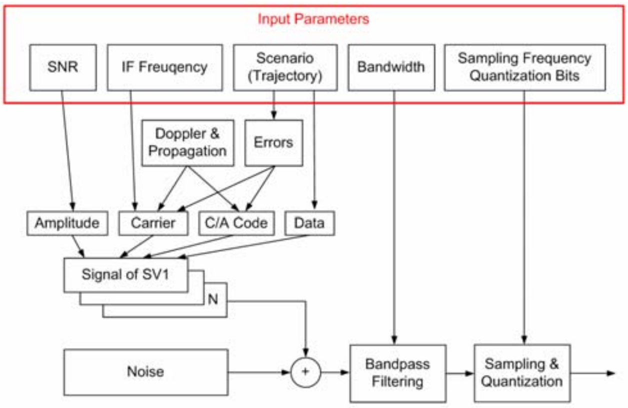


Figure 1. Structure of GPS L1 Signal Generator.

$$\begin{aligned}S_{IF}(t)&=\sqrt{2P}D(t-T_d-\delta t_{IONO}^{L1})C(t-T_d-\delta t_{IONO}^{L1})\\ &\cos(\omega_{IF}t-\omega_{L1}(T_d-\delta t_{IONO}^{L1})+\varphi_0)+N(t)\end{aligned}\tag{1}$$

with

$$T_d=\delta t_{SV}+\delta t_{Eph}+\delta t_{Tropo}+\delta t_P \tag{2}$$

where,

t	is the signal receiving time
P	is the received signal power
D	is the navigation data message
C	is the spreading code
ω_{IF}	is the IF frequency
ω_{L1}	is the L1 frequency
φ_0	is the Initial phase
δt_{IONO}	is the delay due to the ionosphere
δt_{Tropo}	is the delay due to the troposphere
δt_{SV}	is the satellite clock error
δt_{Eph}	is the ephemeris error
t_P	is the propagation delay
$N(t)$	is the Gaussian noise

The tracking error and the receiver clock error are not included in the IF signal model yet, as it is an error happening during tracking. These errors will be investigated in details.

It should also be noticed that equation (1) includes the Doppler information through the term $\omega_{L1}(T_d-\delta t_{IONO}^{L1})$. Because the signal takes some time to travel from the satellite to the receiver antenna, the Earth's rotation (Sagnac effect) has to be taken into account. As in equation (3), each satellite position can be transformed into the common ECI (Earth Centered Inertia) frame using the rotation [1][2].

$$\begin{bmatrix}x_{eci}\\ y_{eci}\\ z_{eci}\end{bmatrix}=\begin{bmatrix}\cos\dot{\Omega}(T_u-T_s) & \sin\dot{\Omega}(T_u-T_s) & 0\\ -\sin\dot{\Omega}(T_u-T_s) & \cos\dot{\Omega}(T_u-T_s) & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}x_s\\ y_s\\ z_s\end{bmatrix}\tag{3}$$

where,

$[x_s \quad y_s \quad z_s]$	is the satellite position in …
$[x_{eci} \quad y_{eci} \quad z_{eci}]$	is the satellite position in …
$\dot{\Omega}$	is the value of the earth's rotation rate
T_u	is the reception time
T_s	is the transmission time for each satellite

Indeed, the GPS IF signal generator uses the receiving time as the reference time. This means that the satellite position at the time of the transmission has to be calculated in order to model the correct range. This is implemented in the receiver part.

The satellite clock error was modeled using the three parameters in the ephemeris data as equation (4) [2].

$$\delta t_{SV}=a_{f0}+a_{f1}(t-t_{OC})+a_{f2}(t-t_{OC})^2+\delta t_{rotation}\tag{4}$$

with

$$\delta t_{rotation}=Fe\sqrt{a}\sin E_k\tag{5}$$

where,

F	is $-4.442807633\times10^{-10}\ s/m^{1/2}$
e	is the satellite orbital eccentricity
a	is the semi-major axis
E_k	is the eccentric anomaly

The ionosphere and troposphere delay models are adapted from the error models used in STR4500^{TM}, they are specified in ICD-GPS-200 and STANAG 4294[3] and known as Klobuchar model and NATO model respectively.

The thermal noise was added taking into account the front-end filter shape. Each satellite C/No could be set individually, allowing different received signal power for each channel. Two bit quantization was used by default, it also can be adjusted by users.

The power level of the received signal is a function of the elevation angle. The GPS system was designed to have the highest received signal power for satellites being at 45 degree elevation. It is reflected in the GNSS IF signal simulator. The relation between received power and elevation angle, without any obstacles, is shown in Figure 2[1].

The antenna gain pattern has a tremendous impact on the signal tracking. Different applications require different antennas. For example, A ship will use antenna with a significant gain at low elevation in order to be able to keep tracking low elevation satellites even in case of high roll. On the other hand, a geodetic antenna will have a very low gain at low elevation in order to reject the potential multipath coming from the ground. One antenna gain pattern is implemented so far in the software GNSS IF signal generator, but any antenna gain pattern can be implemented if other antenna patterns are required.

It can also be used to assess the impact of the antenna on multipath, when combined with the multipath generation module of the software. The antenna with a uniform unit gain is more affected by the multipath, while the antenna in Figure 3 may reduce the effect of multipath because it has lower gain at low elevation angle. In IF signal generator antenna pattern in Fig. 3 is implemented.

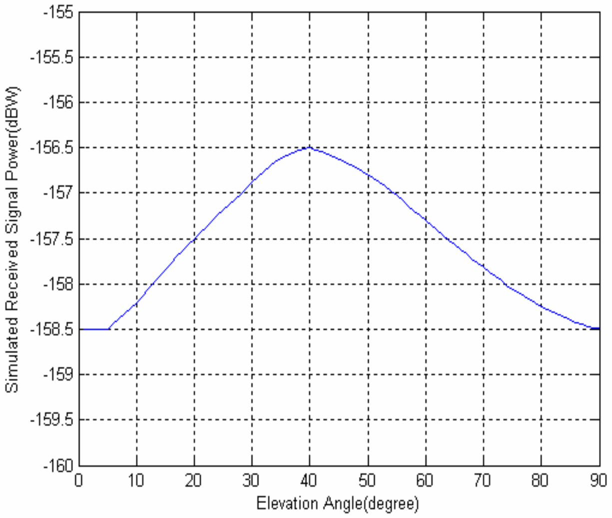


Figure 2. Received Power as a Function of the Elevation Angle.

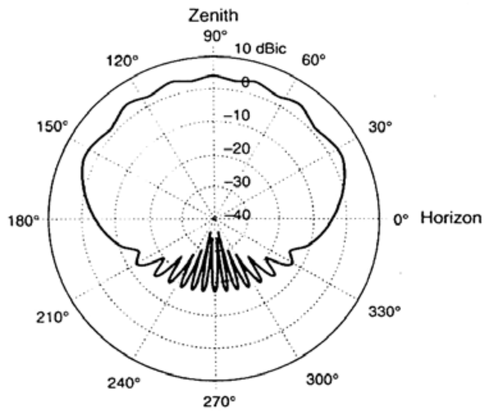


Figure 3. GPS Antenna Gain Pattern.

3. GNSS Signal Generator

The signal generator can provide two signals already fully defined, GPS L1 C/A and GPS L2C, as well as some candidates of the Galileo signals, such as BOC(1,1). These signals can be generated separately or in a combination mode. For example, both L2C and Galileo signals can be generated simultaneously to feed a multi-frequency multi-system software receiver for the test of a combined GPS/Galileo prototype receiver.

The mathematical model of the GPS L1 C/A signal has already been given in Eq. (1). The GPS L2C signal can be represented by the Eq. (6) and the signal generation scheme is summarized in Figure 4 [2]. Eq. (6) includes all errors simulated in the signal generator:

$$\begin{aligned} S_{IF}^{L2C}(t) &= \sqrt{P_{L2C}}\,SB(t-T_d-\delta t_{IONO}^{L2})C_{L2C}(t-T_d-\delta t_{IONO}^{L2}) \\ &\cos(\omega_{IF}t-\omega_{L2}(T_d-\delta t_{IONO}^{L2})+\varphi_0)+N(t) \end{aligned} \quad (6)$$

where,

S_{IF}^{L2C}	is the IF L2C signal
SB	is the symbol after 1/2 FEC
C_{L2C}	is the multiplexed CM and CL code
f_{IF}	is the IF frequency
ω_{L2}	is the L2 frequency angular frequency
δt_{IONO}^{L2}	is the delay due to the ionosphere

The GPS L2C spreading code consists of CM (Civil Moderate) and CL (Civil Long) code. The CM code length is 10,230 chips and chipping rate is 0.5115 MHz. And the CL code length is 767,250 chips and chipping rate is same as the CM code. Because that the CL code does not modulated with navigation data, a tracking is possible using the dataless (i.e. pilot) channel. The availability of the pilot channel allows a coherent carrier tracking that makes the receiver more robust to low C/No and it allows the better acquisition performance. Finally, the GPS L2C signals use convolution encoding, then two data bits should be encoded to one symbol in 1/2 FEC (Forward Error Correction).

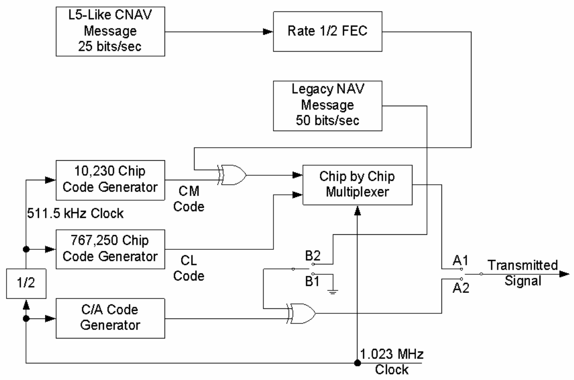


Figure 4. Block Diagram of L2C Signal Generation.

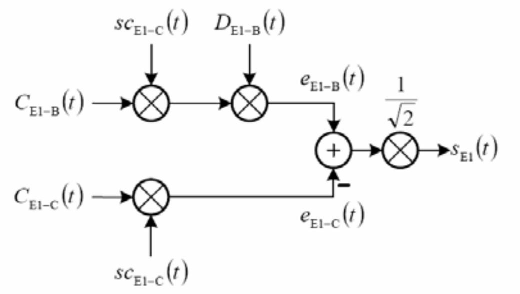


Figure 5. Block Diagram of Galileo E1 Signal Generation.

The Galileo E1 civil signal is generated on L1 frequency with the BOC(1,1) modulation. Figure 5 shows the block diagram for E1 signal generation. The Galileo spreading codes are built using primary and secondary codes, so-called a tiered codes, as in Table 1 [4]. Because the Galileo E1 is composed of both in-phase and quadrature-phase components, 100 PRN codes are needed to generate 50 pairs of BOC(1,1) signal. Using the memory code specified in Galileo OS SIS ICD (Open Service Signal In Space Interface Control Document), 12 satellite signals can be generated simultaneously.

Table 1. Code characteristics of Galileo signal

Channel	Code Length (ms)	Code length (chips)	
		Primary	Secondary
E5a-I	20	10230	20
E5a-Q	100	10230	100
E5b-I	4	10230	4
E5b-Q	100	10230	100
E1-B	4	4092	-
E1-C	100	4092	25

The mathematical model for the BOC(1,1) signal are represented as follows:

$$\begin{aligned} S_{IF}^{E1}(t) &= \sqrt{P_{E1}}\,D_{E1\_B}(t-T_d-\delta t_{IONO}^{L1})SC_{E1\_B}(t-T_d-\delta t_{IONO}^{E1}) \\ &C_{E1\_B}(t-T_d-\delta t_{IONO}^{E1})\cos(\omega_{IF}t-\omega_{L1}(T_d-\delta t_{IONO}^{E1})+\varphi_0) \\ &+\sqrt{P_{E1}}\,SC_{E1\_C}(t-T_d-\delta t_{IONO}^{E1})C_{E1\_C}(t-T_d-\delta t_{IONO}^{E1}) \\ &\sin(\omega_{IF}t-\omega_{L1}(T_d-\delta t_{IONO}^{E1})+\varphi_0)+N(t) \end{aligned} \quad (7)$$

where,

S_{IF}^{E1}	is the IF E1 signal
D_{E1}	is the navigation data
SC	is the Rectangular Subcarrier

C_{E1_I} is the In-phase E1 PRN code

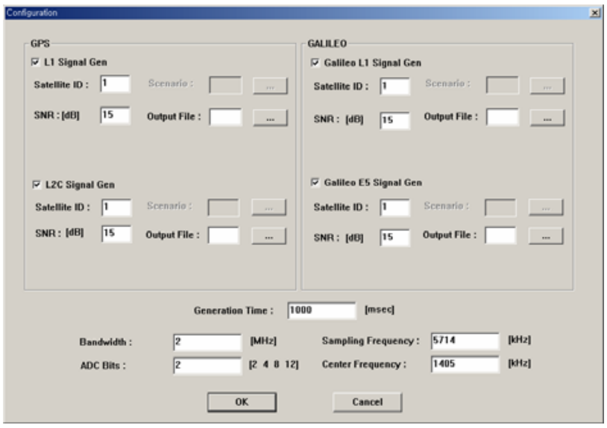
C_{E1_Q} is the Quadrature-phase E1 PRN code

A tiered code is implemented on each data and dataless channel based on the latest Galileo E1 civil signal structure.

4. Verification of the Generated Signals

The user interface of the GNSS IF signal generator is shown in Figure 6. Users can generate GPS L1 C/A, GPS L2C and Galileo E1 signal. Galileo E5 signal is under construction and it will be generated in near future. Users can adjust many parameters such as sampling frequency, IF frequency, bandwidth and quantization bits and so on.

The power spectral density of generated signals is analyzed to verify the output of IF signal generator. The power spectral density of GPS L1 C/A signal is shown in Figure 7. The main lobe has a sinc envelope and a width of 10.23 MHz as expected. The ratio between the GPS L1 C/A code chipping rate and the code length equals 0.001, it means that it has spectral rays every 1 KHz. As the CM/CL code has the same chipping rate as C/A code, its power spectral density shown in Figure 8 is similar to that of L1.



☑ L1 Signal Gen

Satellite ID : 1

SNR : [dB] 15

☑ L2C Signal Gen

Satellite ID : 1

SNR : [dB] 15

☑ Galileo L1 Signal Gen

Satellite ID : 1

SNR : [dB] 15

☑ Galileo E5 Signal Gen

Satellite ID : 1

SNR : [dB] 15

Generation Time : 1000 [msec]

Bandwidth : 2 [MHz]

ADC Bits : 2 [2 4 8 12]

Sampling Frequency : 5714 [kHz]

Center Frequency : 1405 [kHz]

Figure 6. User Interface of GNSS IF Signal Generator.

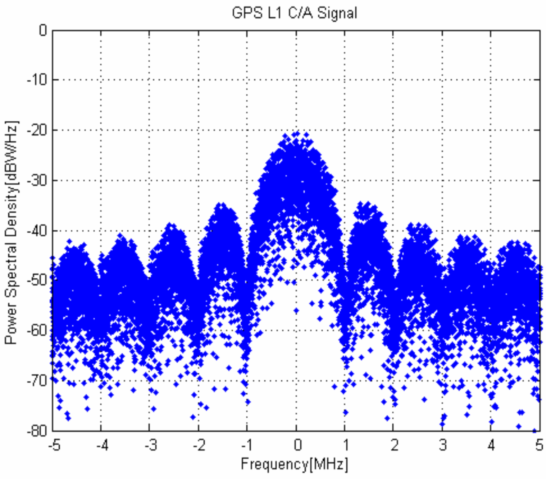


Figure 7. Power Spectral Density of GPS L1 C/A Signal.

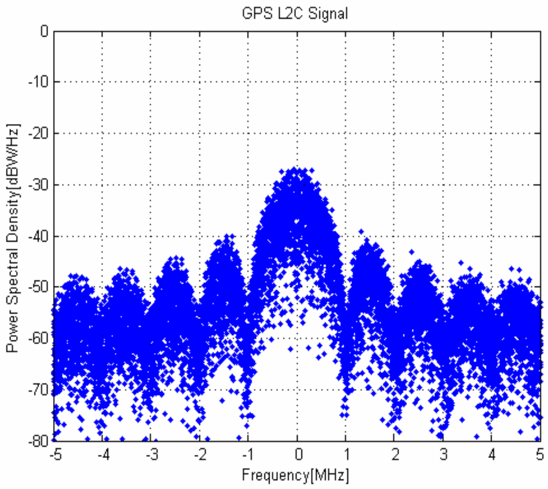


Figure 8. Power Spectral Density of GPS L2C Signal.

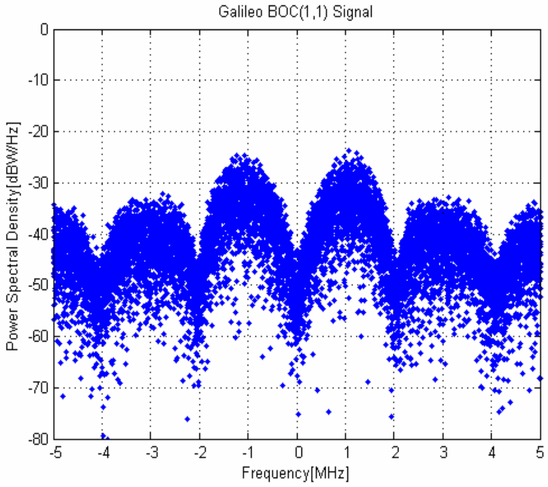


Figure 9. Power Spectral Density of Galileo BOC(1,1) Signal.

Figure 9 shows the power spectral density of generated Galileo BOC(1,1) signal. The power is mainly distributed in the two split spectrum and it is 3dB lower than the power of L1 C/A signal as expected.

Generated signals also are processed in the real software receiver to evaluate the correctness. Acquisition and tracking abilities are analyzed in this paper.

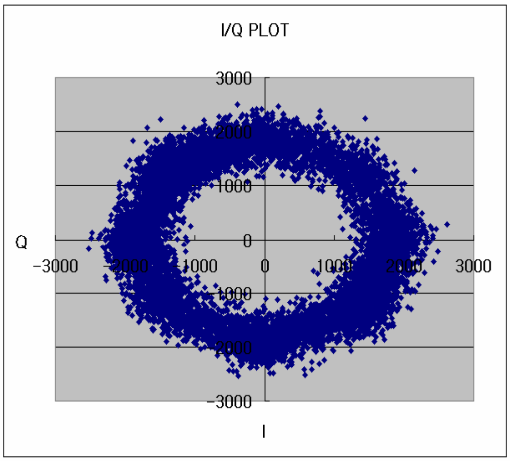


Figure 10. I/Q Plot of L1 Signal in tracking status.

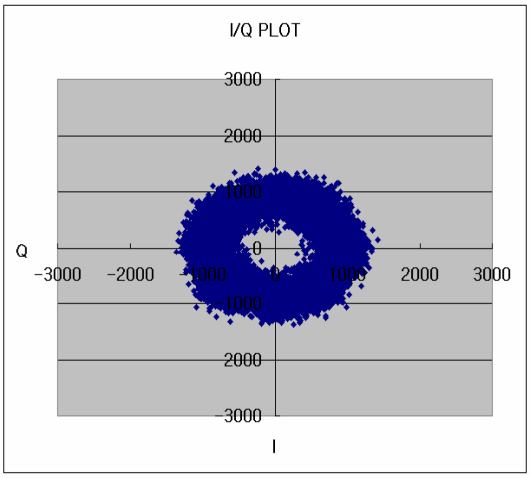


Figure 11. I/Q Plot of BOC Signal in tracking status.

Figure 10 and Figure 11 show the I/Q plot of GPS L1 C/A code and BOC(1,1) code. FLL (Frequency Lock Loop) is used to track signals.

These figures show that the implemented GNSS IF signal generator is correctly working and the result obtained by using the generator is reliable.

5. Conclusions

In this paper, a design and implementation of a software IF GNSS signal generator is given. The signal generator is very versatile and useful tool which can be applied to a diversity of researches and developments. It includes the modeling of not only GPS and Galileo signals but also all the major sources of errors affecting GNSS signal reception such as satellite clock errors, atmospheric effects and thermal noise. The enhancement brought by the implementation of a realistic received power gain pattern and antenna gain pattern makes this IF signal generator very useful to evaluate interference mitigation .techniques.

The object-oriented implementation makes easy the addition and modification of more advanced modules, such as the generation of L2C signal and Galileo BOC(1,1) signal. This software IF GNSS signal generator has already been proven to be very effective in the development of signal processing algorithms in GNSS receivers because of its high flexibility. It is an efficient tool to test new software receiver-based algorithms in real environment without the need of a hardware signal simulator for a variety of tasks, ranging from interference to indoor tracking.

References

1. Elliott D. Kaplan, *Understanding GPS Principles and Application*, 2nd Edition, Artech House, 2005.
2. *IS-GPS-200, Navstar GPS Space Segment/Navigation User Interfaces*, December, 2004
3. SPIRENT, *STR4500 GPS/SBAS SIMULATOR WITH SimPLEX SOFTWARE USER MANUAL*, May, 2004
4. European Space Agency, *Galileo Open Service Signal In Space Interface Control Document(OS SIS ICD) Draft 0*, 2006