# Hybrid GPS/Galileo/GLONASS IF Software Signal Generator

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**BIOGRAPHY**

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René Jr. Landry received a PhD degree at SupAéro / Paul-Sabatier University and a Post Doc in Space Science at the National French Space Industry (CNES), both at Toulouse, France, in 1997 and 1998 respectively. Since 1999, Professor Landry is involved in receiver design and the problem of navigation and telecommunication signal interferences for the Canadian Navigation and Communication Industries. One of his major interest concerns the development of New Innovative Mitigation Techniques for GNSS Receiver Robustness Design including those of electronic Inertial Navigation System based on low cost MEMS. He is actually working on several digital signal processing applications in Anti-Jamming, receiver design, Indoor Navigation and Inertial Navigation Systems.

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**ABSTRACT**

A Global Navigation Satellite System (GNSS) signal simulator is a necessity for the development and validation phases of a GNSS receiver. By connecting the simulator to the antenna port of a receiver, the latter can navigate as if it is on a real vehicle. Indeed, there are many other advantages for using such a simulator. For example, the same simulation scenarios can be run repeatedly until the desired outcomes are achieved. Also, the simulator would allow testing GNSS receivers in various environments and characterizing the receiver's behavior in unusual or unexpected conditions. The efficiency of the receiver's development is ensured by working in a controlled and repeatable test environment.

A hybrid GNSS receiver requires the GPS, Galileo and/or GLONASS signals as input. Hence, the design process of hybrid receivers requires a hybrid signal simulator that can generate the GPS, Galileo and/or GLONASS signals. Specifically, the hybrid signal simulator should generate the following signals: GPS L1 and L5, Galileo E5a, E5b and E6, GLONASS L1 and L2 signals. However, the cost of such a simulator is very high and not all functionalities are available. The need for low-cost reprogrammable signal generators is becoming urgent in several fields (e.g. geomatics engineering) and a low-cost software defined hybrid signal simulator would be an enormous asset for the development of hybrid receivers. As the Galileo satellite constellation and signal generation are still in the development phase, GPS will be modernized and GLONASS updated, the GNSS signal simulator should be very flexible and should give the possibility for easy updates and changes in order to be as much realistic as possible.

This paper presents a software IF signal generator called IF Software Defined Signal Simulator (SDSS), which has been developed in Matlab/Simulink and the platform is under implementation and test in FPGA (Field Programmable Gate Array). The simulator allows the user to control many parameters, such as the choice of the disturbance and propagation channel parameters, various pre-defined environments, etc.

## 1. INTRODUCTION

The advent of the European Galileo navigation system, the modernization of the American GPS and the update of the GLONASS satellite constellation will lead to an improved GNSS. Further, the deployment of Galileo as a second, independent and interoperable satellite navigation

system will certainly help the GNSS consumer market to increase. This is due to the fact that, the interoperability between GPS and Galileo will help to overcome some of the GPS shortfalls such as service guarantees, integrity monitoring, improved service performance and signal, search and rescue.

The Galileo system provides a lot of potential for innovative developments. One of the main challenges is the design of a hybrid GNSS signal simulator. As the Galileo satellite constellation and signal generation are still in the development phase, the GNSS signal generator should be very flexible and should give the possibility for easy updates and changes in order to be as much realistic as possible. The GNSS signal simulator should also be able to allow easy and fast modifications when the Galileo signals will be available, for a better realism of the signal generation.

Signal simulators are sophisticated electronic devices specifically designed to generate artificial "RF signals in space". The idea is to produce RF signals in the "office environment" that are identical to those a GNSS receiver would see in a real application. A comprehensive simulation environment requires the full control and the repeatability of every scenario. Thus, identical simulation scenarios can be run repeatedly until all the desired outcomes are achieved. A signal simulator is the perfect tool for design, development and testing of GPS/Galileo/GLONASS products or their integration.

Different approaches have been proposed in the literature for the design of a GNSS signal simulator [JUL04]. Also, there are some companies who have commercialized such kind of simulators, such as Spirent Communications and Cast Navigation.

In this paper, an Intermediate Frequency (IF) hybrid GNSS signal generator, called IF Software Defined Signal Simulator (SDSS) is presented, as well as the receiver trajectory generation, the propagation and disturbance channel and the interference signal generator. The final IF simulator will include also the front-end modeling and it will be able to provide sampled data to a hybrid receiver for navigation test purposes. The IF hybrid signal simulator presented in this paper has been developed in Matlab/Simulink and is currently under implementation partly in a FPGA.

The structure of the IF SDSS signal proposed in this paper consists in the following 5 main parts: (1) GPS/Galileo/GLONASS satellite constellation generation; (2) receiver trajectory generation; (3) GPS/Galileo signals generation; (4) propagation and disturbance channel; (5) interference signal generator.

The test of hybrid GNSS receivers can be done by using either real satellite signals or signals coming from an RF hardware GNSS signal generator. The latter are very useful especially in a R&D environment or for future GNSS signals, which are not yet available from real satellites. GNSS receivers are tested with RF signals sampled using a RF front-end. A simpler, less expensive and very flexible way in testing GNSS receivers is to provide the receiver with the corresponding data at an Intermediate Frequency (IF) from a software IF GNSS signal generator.

The SDSS simulator allows the user to define and to specify its own mission scenarios and environments. Also, it allows a wide range of various tests, such as the influence of various pre-defined environments (e.g. the atmospheric effects, multipath) on the receiver performances. Hence, the SDSS simulator would be an asset for the design, test and analysis of hybrid GNSS receivers.

Benefits of the development of such a simulator can be expected for the design of new GPS/Galileo/GLONASS receivers using multiple frequencies, such as Safety-of-Live applications receivers. The signal generator presented in this paper is an IF signal simulator having several advantages in the GNSS technology development. The efficiency of the development is ensured by working in a controlled and repeatable test environment. The SDSS simulator can characterize the receiver's behavior in unusual or unexpected conditions.

The paper is organized as following. In Section 2 the GNSS (GPS, Galileo and GLONASS) parameters are briefly introduced. Section 3 is dedicated to the presentation of the actual and modernized GPS and future Galileo signals. Section 0 is dedicated to the presentation of the architecture of the IF SDSS simulator, which represents the main part of the paper. It includes the description of the hybrid GNSS constellations implementation, the GNSS signal generator, the receiver trajectory generation, the propagation and disturbance channel (including the ionosphere and troposphere models, multipath, etc.) and the interference signal generator. Section 5 presents some results obtained with the IF SDSS simulator. The last section of the paper is dedicated to some conclusions and perspectives.

## 2. GNSS CONSTELLATIONS PARAMETERS

### 2.1. GPS CONSTELLATION PARAMETERS

The GPS constellation comprises 24 satellites located on nearly circular orbits, with a radius of 26561.75 km and a period of 11 h 58 min (half of a mean sidereal day). The satellites are situated on 6 orbital planes (named A through F) inclined at 55° relative to the equatorial plane (4 satellites per orbit, named 1 through 4). The satellite planes are equally spaced in longitude relative to the vernal equinox, but the satellites themselves in each plane are not equally spaced. The GPS constellation parameters may be found in [PAR96, KAP96] and additional information in [MIS01, MAS98, KEL98].

## 2.2. Galileo Constellation Parameters

The space segment of Galileo consists of 27 Mean Earth Orbiting (MEO) satellites, distributed over 3 orbital planes (named A through C) with a period of 14 h 21 min (3/5 of the mean sidereal day). There are 9 satellites per orbit, named 1 through 9. The Galileo constellation parameters are presented in Table 1. No information has been found concerning the phase of the Galileo planes with respect to the GPS ones (the parameters presented in Table 1 have been considered, without any additional correction).

| Semi-Major Axis [km] | 29600.318 |
|---|---|
| Inclination [°] | 56 |

| Satellite ID | Right Ascension [°] | Mean Anomaly [°] |
|---|---|---|
| A1,A2,A3,A4,A5, A6,A7,A8,A9 | 0 | 0, 40, 80, 120, 160, 200, 240, 280, 320 |
| B1,B2,B3,B4,B5, B6,B7,B8,B9 | 120 | 13.33, 53.33, 93.33, 133.33, 173.33, 213.33, 253.33, 293.33, 333.33 |
| C1,C2,C3,C4,C5, C6,C7,C8,C9 | 240 | 26.66, 66.66, 106.66, 146.66, 186.66, 226.66, 266.66, 306.66, 346.66 |

**Table 1:** Galileo constellation parameters

For more details on the nominal Galileo constellation see [SAL01].

## 2.3. GLONASS Constellation Parameters

The GLONASS satellite constellation consists of 24 satellites, distributed over 3 orbital planes (named A through C) with a period of 11 h 15 min. There are 8 satellites per orbit, named 1 through 8. The GLONASS constellation parameters are presented in Table 2.

| Semi-Major Axis [km] | 25510 |
|---|---|
| Inclination [°] | 64.8 |

| Satellite ID | Right Ascension [°] | Mean Anomaly [°] |
|---|---|---|
| A1,A2,A3,A4, A5,A6,A7,A8 | 0 | 0, 45, 90, 135, 180, 225, 270, 315 |
| B1,B2,B3,B4, B5,B6,B7,B8 | 120 | 15, 60, 105, 150, 195, 240, 285, 330 |
| C1,C2,C3,C4, C5,C6,C7,C8 | 240 | 30, 75, 120, 165, 210, 255, 300, 345 |

**Table 2:** GLONASS constellation parameters

For more details on the nominal GLONASS constellation see [ICD88].

## 3. GNSS SIGNALS

Multiple frequency transmissions represent the near future of the civil satellite navigation systems. In this section, the main characteristics of the GPS and Galileo signals are presented.
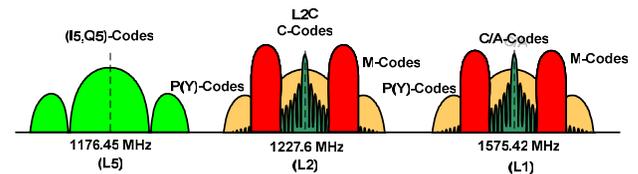
## 3.1. GPS Signals

The current civil GPS signal has been designated as L1 and it consists of a single frequency transmission at 1575.42 MHz. Figure 1 shows the current GPS L1 and L2 frequencies and the corresponding signals: 1 civil signal, C/A-Code on L1, and 2 military signals, P-Code on L1 and L2.
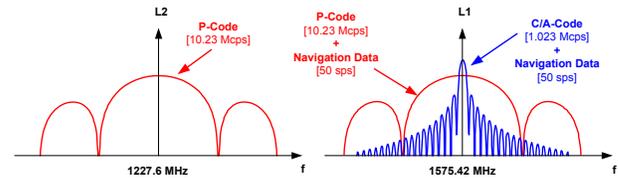


**Figure 1:** Current GPS signals

In the future, there will be also a civil signal in the L2 band which is at 1227.6 MHz, where only a military signal exists currently. Also, a third civil frequency signal is scheduled at 1176.45 MHz, designated as L5 (the first launch is scheduled before the end of 2005 and the full operational availability around 2012) [CLI03].

Figure 2 presents the evolution of the GPS signals in accordance with the modernization program proposed [DON02, SHA02]. This program consists in the launch of the first block satellites from 2003 to 2006 for the L2C and two military signals (M-codes). The satellites of the second block will allow the launch of the new L5 civil signal. The three frequencies, L1, L2 and L5, will contain the following signals: 3 civil signals (C/A-Code on L1, C-Code on L2, (I5,Q5)-Codes on L5) and 4 military signals (P-code on L1 and L2, M-Code on L1 and L2).
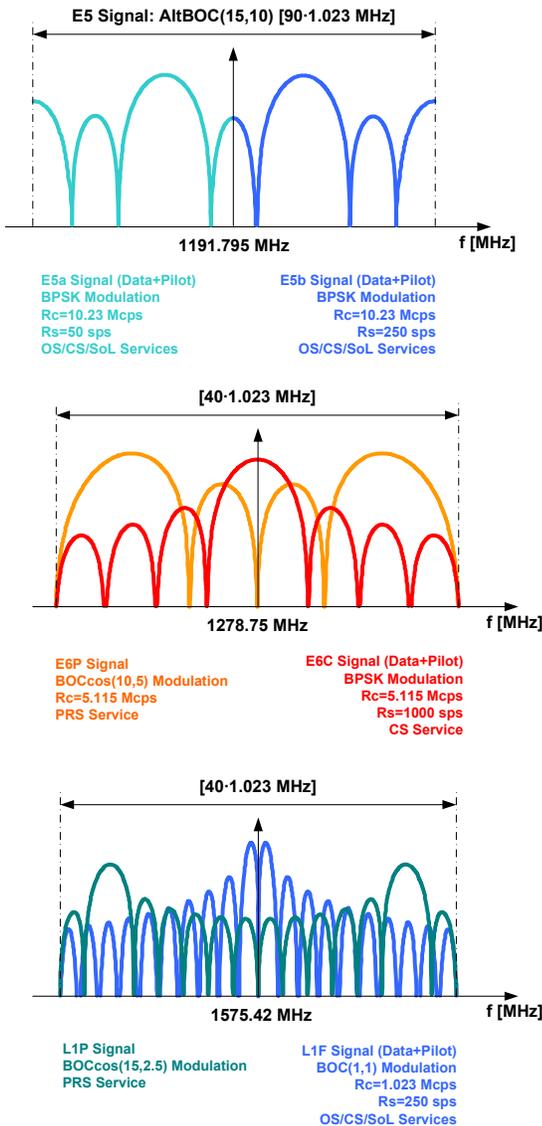


**Figure 2:** GPS signals evolution

## 3.2. Galileo Signals

In Europe, Galileo has been designed as a multiple civil frequency satellite navigation system. The Galileo signals will be transmitted on the E2-L1-E1, E5a, E5b and E6 frequencies. The use of the same center frequencies as GPS on E5a (L5) and E2-L1-E1 (L1) provides a very good interoperability for a future hybrid GPS/Galileo satellite navigation system.

The Galileo system will transmit 10 navigation signals in several frequency bands which are presented in Figure 3 and Figure 4 [ICD05, HEI02]. These signals are:

- Six signals (three of them being data-free) available to Galileo users on the E5a, E5b and L1 carrier frequencies for Open Services (OS) and Safety-of-Life (SoL).

- Two signals with encrypted ranging codes (one of them being data-free) accessible only to some dedicated users of the Commercial Service (CS).

- Two signals, one in L6 and the other in E2-L1-E1 with encrypted ranging codes and data, accessible to authorized users of the Public Regulated Service (PRS).



**E5 Signal: AltBOC(15,10) [90·1.023 MHz]**

1191.795 MHz    f [MHz]

E5a Signal (Data+Pilot)
BPSK Modulation
Rc=10.23 Mcps
Rs=50 sps
OS/CS/SoL Services

E5b Signal (Data+Pilot)
BPSK Modulation
Rc=10.23 Mcps
Rs=250 sps
OS/CS/SoL Services

**[40·1.023 MHz]**

1278.75 MHz    f [MHz]

E6P Signal
BOCcos(10,5) Modulation
Rc=5.115 Mcps
PRS Service

E6C Signal (Data+Pilot)
BPSK Modulation
Rc=5.115 Mcps
Rs=1000 sps
CS Service

**[40·1.023 MHz]**

1575.42 MHz    f [MHz]

L1P Signal
BOCcos(15,2.5) Modulation
PRS Service

L1F Signal (Data+Pilot)
BOC(1,1) Modulation
Rc=1.023 Mcps
Rs=250 sps
OS/CS/SoL Services

**Figure 3:** Galileo navigation signals overview

All these frequency bands are located in the spectrum allocated for Radio Navigation Satellite Services (RNSS). The E5a, E5b, and E2-L1-E1 bands are located also in the spectrum allocated for Aeronautical Radio Navigation Services (ARNS) used in aviation (SoL applications).

Two frequency bands (E2-L1-E1 and E5a) have been chosen common to the current GPS L1 and the future GPS L5 bands. The use of the same carrier frequencies in these bands increases the interoperability and compatibility between GPS and Galileo.

All Galileo satellites will share the same frequency bands by using Code Division Multiple Access (CDMA). Spread-spectrum signals will be transmitted in Right-Hand Circular Polarization (RHCP). Four different types of data will be carried by the various Galileo signals:

- OS data, transmitted on the E5a, E5b and E2-L1-E1 carrier frequencies. These data will be accessible to all users.

- CS data, transmitted on the E5a, E5b, E6 and E2-L1-E1 carriers. All CS data will be encrypted.

- SOL data, transmitted on E5a, E5b and E2-L1-E1.

- PRS data, transmitted on the E6 and E2-L1-E1 carrier frequencies.

For more information on the Galileo signals see [ICD05, HEI02].

### 3.3. GPS AND GALILEO SIGNALS

An overview of the actual and future GPS and Galileo signals and the corresponding frequencies are given in Table 3.

| System | Signal | Frequency [MHz] | Frequency [x10.23MHz] |
|--------|--------|-----------------|------------------------|
| **GPS** | L1 | 1575.420 | 154 |
| | L2 | 1227.600 | 120 |
| | L5 | 1176.450 | 115 |
| **Galileo** | L1 | 1575.420 | 154 |
| | E5a | 1176.450 | 115 |
| | E5b | 1207.14 | 117.5 |
| | E6 | 1278.75 | 125 |

**Table 3:** Overview of available and future GPS and Galileo signals

The evolutions of the GPS, Galileo and GLONASS frequency spectrums are presented in Figure 4 [EIS02, ICD05].

### 3.4. GLONASS SIGNALS

Each GLONASS satellite transmits navigation signals in two sub-bands of L-band (L1~1.6 GHz and L2~1.2 GHz) [ICD88].

GLONASS uses Frequency Division Multiple Access (FDMA) technique in both L1 and L2 sub-bands. This means that each satellite transmits navigation signal on its own carrier frequency in the L1 and L2 sub-bands. Two GLONASS satellites may transmit navigation signals on the same carrier frequency if they are located in antipodal slots of a single orbital plane.

GLONASS satellites provide two types of navigation signals in the L1 and L2 sub-bands: standard accuracy signal and high accuracy signal.
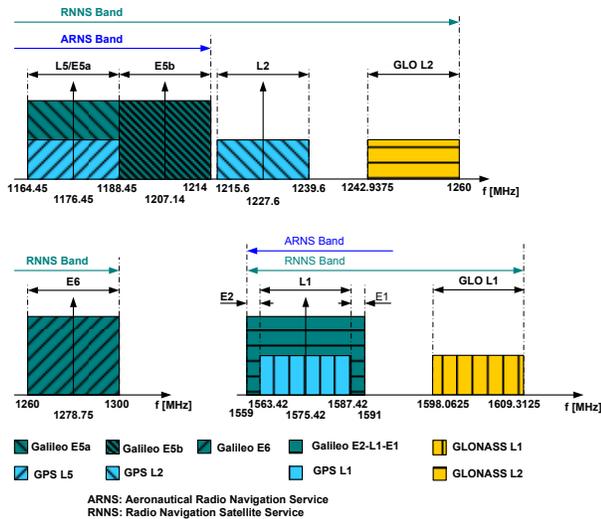
**Figure 4:** Evolutions of GPS and Galileo signals

The standard accuracy signal with clock rate 0.511 MHz is designed for using by civil users worldwide. The high accuracy code with clock 5.11 MHz is modulated by special code. The standard accuracy signal is available for any users equipped with proper receivers and having visible GLONASS satellites above the horizon.

## 4.  IF SDSS SIMULATOR

The development environment used for the SDSS Simulator is Matlab/Simulink which allows fast implementation, easy signal processing and graphical representation, as well as VHDL coding for the FPGA implementation which is currently in progress. In addition, the simulator may be controlled via friendly Graphical User Interface (GUI), which allows the user to do parameters configurations, simulations and results analysis.

Among various objectives of the simulator, the following ones are the most important: (a) evaluation and performance analysis of hybrid GNSS constellations; (b) evaluation and analysis of new signal processing techniques for the new GNSS signal structures; (c) optimization of receiver design implementation and signal processing, based on the simulated GNSS signals.

The SDSS simulator has four main features: (a) GNSS (GPS-Galileo-GLONASS) satellite constellation simulator; (b) mobile/receiver trajectories generation (navigation), which may be obtained by using Microsoft Flight Simulator or X-Plane, as well as by defining user parameterized trajectories; (c) hybrid signal generator for the various GNSS frequencies; (d) interference signal generator.

As the advent of the European Galileo system represents a critical issue in the actual navigation R&D international community, the design of the simulator has been focused first on the development of the GPS and Galileo signals, which has an important priority for us. Nevertheless, the

GLONASS satellite constellation is already implemented in the simulator and the generation of the signals will be considered in the near future.

Due to the fact that the Galileo signals are not defined completely yet, the definition of a software defined signal generator would be one of the best approaches for the SDSS simulator design. The simulator allows the user to control many parameters and to choose the simulation configuration (e.g. choice of the GNSS configuration and signals to simulate, the disturbance and propagation channel parameters, the interference parameters, etc.). An important advantage of the SDSS simulator is the access to any parameter and at any hierarchical level.

The final version of the IF SDSS simulator presented in this paper will include also the front-end modeling and it will be able to provide data to a hybrid receiver.

The main architecture of the IF SDSS simulator is presented in Figure 5.
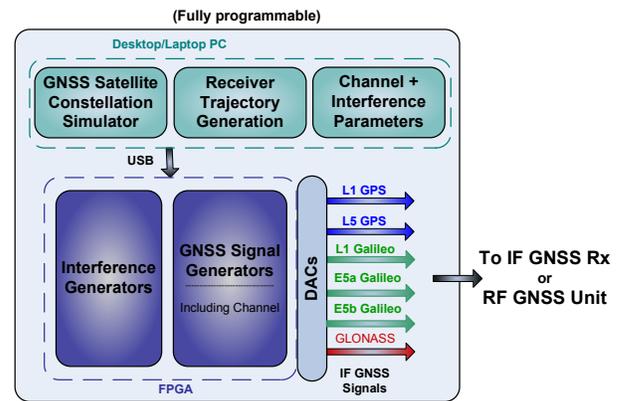


**Figure 5:** Architecture of the IF SDSS simulator

The structure of the IF SDSS simulator consists of the following 5 main parts:

1. GPS/Galileo/GLONASS satellite constellation generation (see Section 4.1). The latest available values of Right Ascension of the Ascending Node (RAAN) and mean anomalies have been considered for the Galileo satellite navigation system (the initial offset of GPS and Galileo orbital planes is programmable). At the same time, almanac or broadcast ephemeris files have been used in order to generate the GPS satellite constellation. Note that analysis and validation of the hybrid satellite constellation generation have been presented in other publications [CON05] and they are not considered in this paper.

2. Receiver trajectory generation (see Section 4.2). The receiver trajectory and the hybrid satellite constellation simulation allow the computation of the Doppler frequencies for each satellite (carrier and code), the satellites azimuth and elevation, the various Dilution Of Precision (DOP) values, etc.

3. GPS and Galileo signals generation. The signal generator provides the following signals: GPS L1 and L5 (see Sections 4.3 and 3), Galileo E2-L1-E1 and E5a/E5b (see Sections 4.4 and 3) and, in the near future, GLONASS L1 and L2 [ICD88].

4. Propagation and disturbance channel (see Section 4.5).

5. Interference signal generator (see Section 4.6).

The generation of the GNSS satellite constellation, the receiver trajectory as well as the parameters for the disturbance channel and the interference signals are computed on a desktop/laptop PC. The generation of the GNSS signals including the propagation and disturbance channel effects, as well as the interference signals are implemented in a FPGA (see Figure 5).

A more detailed block diagram of the desktop/laptop PC architecture is presented in Figure 6.
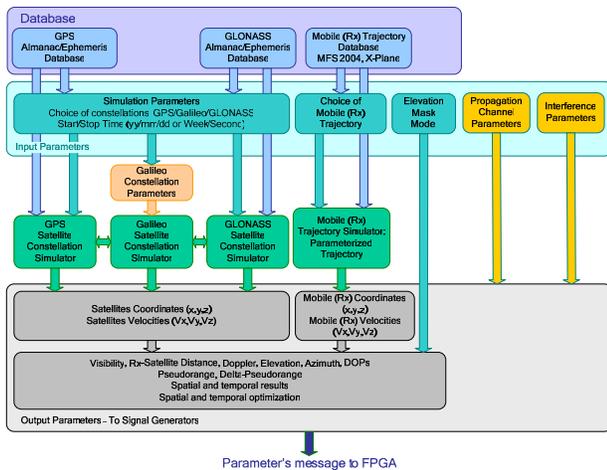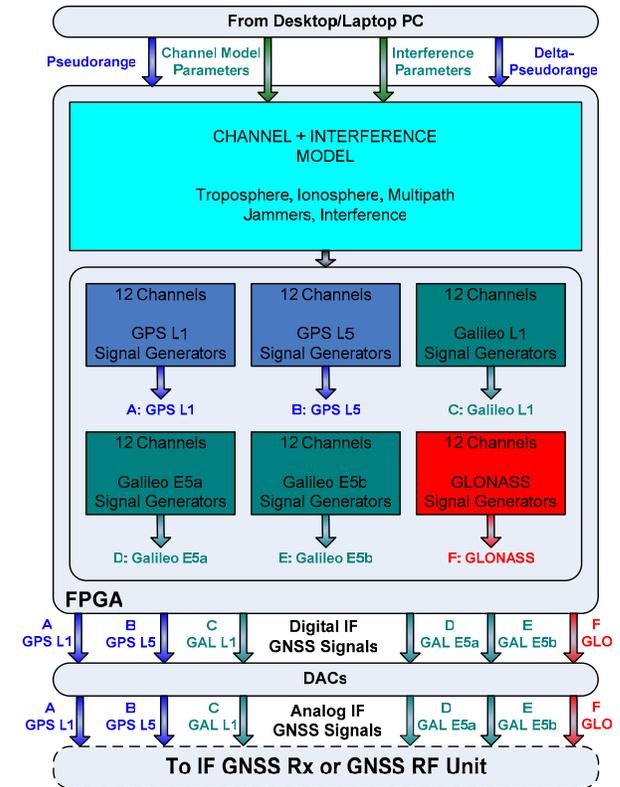


**Figure 6:** PC implementation – GNSS satellite constellation and receiver trajectory

The generation of the satellite constellations and the receiver trajectory allows the user to evaluate the hybrid GNSS constellations performances, such as visibility, elevation, azimuth, DOPs. It also allows performing spatial and temporal optimizations and analysis from different performance parameters point of view. In addition, it allows computing all the parameters necessary for the generation of the various GPS/Galileo signals, such as pseudorange and delta-pseudorange. For more details on the GNSS satellite constellations implementation, validation, performances and features see [CON05, CON04].

In the final version of the IF SDSS simulator, the various GNSS interference signals will be generated in a FPGA. The proposed architecture of the FPGA implementation is presented in Figure 7.

The IF simulator contains 12 channels for each navigation signal and can be used by a RF amplification unit. More

details on the implementation of the IF SDSS simulator are presented in the next sections.



**Figure 7:** FPGA implementation – IF Signal Generators

## 4.1. CONSTELLATIONS IMPLEMENTATION

### 4.1.1. GPS Constellation Implementation

The GPS satellite constellation implementation is based on either GPS constellation parameters (see Section 2.1) or on almanac and broadcast ephemeris files. The GPS satellite constellation based on almanac and ephemeris files has been validated with precise ephemeris data and with data from a real GPS receiver. The validation results and implementation details may be found in [CON05].

### 4.1.2. Galileo Constellation Implementation

As the Galileo almanac and broadcast ephemeris files are not yet available, the Galileo satellite constellation implementation is based on the parameters presented in Section 2.2, Table 1.

### 4.1.3. GLONASS Constellation Implementation

The GLONASS satellite constellation implementation is based on the parameters presented in Section 2.3, Table 2 (in the future, the GLONASS constellation will be implemented based on almanac and broadcast ephemeris files).

## 4.2. RECEIVER TRAJECTORY GENERATION

The generation of the mobile/receiver trajectory can be achieved by using either Microsoft Flight Simulator or the X-Plane software. Also, the user has the possibility to consider parameterized trajectories and to change the various parameters of these trajectories. In addition, the user can use pre-defined trajectories or select pre-defined realistic missions.

The simulator provides also the possibility to either specify an elevation mask which corresponds to the receiver's environment, or choose a pre-defined elevation mask model (elevation mask as function of the azimuth), among several models corresponding to various environments (e.g. urban canyons).

## 4.3. GPS SIGNAL GENERATOR

### 4.3.1. GPS L1 Signal Generator

The GPS satellites transmit a Right Hand Circularly Polarized (RHCP) L-band signal known as L1 at 1575.42 MHz. The C/A-code has been considered in the SDSS simulator for the GPS L1 signal.

L1 is Bipolar-Phase Shift Key (BPSK) carrier modulated with a Pseudo Random Noise (PRN) code at 1.023 MHz, known as the C/A code. This C/A code sequence repeats every ms. The transmitted equence is actually the modulo-2 addition of a 50-Hz navigation message and the C/A code. More details on the GPS L1 signal can be found in [ICD93, PAR96, KAP96].

### 4.3.2. GPS L5 Signal Generator

As already mentioned in Section 3.1, the GPS system will feature a new civil signal with a bandwidth of 24 MHz. The full operational availability of the L5 signal is scheduled for 2012. The new GPS L5 signal is QPSK-modulated and centered on 1176.45 MHz (115 × 10.23 MHz).

The two L5 components, in-phase I5 and quadrature Q5, have each a different spreading code of 1 ms in length at a chipping rate of 10.23 Mcps. CDMA techniques allow differentiating between the SVs even though they all transmit at the same L5 frequency. For each code, the 1-ms sequences are the modulo-2 sum of two sub-sequences of 8,190 chips and 8,191 chips of length, respectively. The GPS L5 modulation is shown in **Figure 8**.
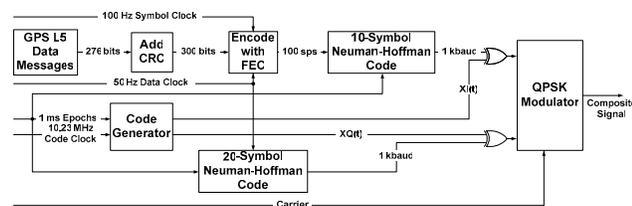


**Figure 8:** GPS L5 signals modulation

As it may be seen in **Figure 8**, the 100 sps symbols are modulated with a 10-bit Neuman-Hoffman code at 1 kHz.

The resultant composite signal is then used to modulate the L5 in-phase carrier (I5). The Q5-code is modulated with a 20-bit Neuman-Hoffman code that is also at 1 kHz. The Q5 component (pilot) does not carry any message at all.

The L5 signal consists of two carrier components that are in phase quadrature with each other. Each carrier component is BPSK modulated by separate signals. One signal is the modulo-2 sum of the I5-code, navigation data, and synchronization sequence while the other is the Q5-code with no navigation data, but with another synchronization sequence.

For more information on the GPS L5 signal properties see [ICD01, DIE00, RIE02b, BAS04].

## 4.4. GALILEO SIGNAL GENERATOR

### 4.4.1. Basis of Galileo Signals [RIE02a]

**Standard Binary Offset Carrier (BOC) signal**

An Offset Carrier (OC) signal results from the modulation of a Non Return to Zero (NRZ) PRN sequence by a sub-carrier. In the following, $R_{C/A} = 1.023$ MHz is assumed to be the C/A code rate. A PRN sequence with a chip rate $R_c = f_c \cdot R_{C/A}$ modulated by a square sub-carrier of frequency $R_s = f_s \cdot R_{C/A}$ ($R_s \geq R_c$) is defined as a BOC($f_s, f_c$), where $f_s$ and $f_c$ are not necessarily integers.

The effect of the square sub-carrier is to split the main lobe of the PRN code spectrum into two lobes centered at $\pm R_s$ from the central frequency. When $f_s$ and $f_c$ are integers, the associated BOC($f_s, f_s$) is a Manchester code. A BOC signal is usually generated in baseband and then modulates a RF carrier.

**Alternative-BOC (AltBOC) signals**

An AltBOC signal is a BOC-like signal having different PRN codes in the lower and the upper main split lobes. It allows one signal service per lobe. If the two PRN codes of an AltBOC are made identical, the signal becomes a classical BOC. For more information on AltBOC signals see [RIE02a, ISS03, KRE04].

The purpose of the alternative BOC is to generate a single sub-carrier signal adopting a source coding similarly to the one involved in the classical BOC. This allows keeping the BOC implementation simplicity, as well as differentiating the lobes.

### 4.4.2. Galileo E2-L1-E1 Signal Generator

The L1 signal contains three channels that are transmitted at the same carrier frequency (L1 = 1575.42 MHz) using a modified hexaphase modulation [HEI02] (see Figure 9).

The Galileo E2-L1-E1 signal can be written as follows:

$$S_{L_1}(t) = \left[ C_{L_1}^A(t) \cdot D_{L_1}^A(t) \cdot Sc_{L_1}^a(t) \cdot \cos(m) - C_{L_1}^C(t) \cdot Sc_{L_1}^b(t) \cdot \sin(m) \right] \times \cos(2\pi \cdot F_{L_1} \cdot t)$$
$$- \left[ C_{L_1}^B(t) \cdot D_{L_1}^B(t) \cdot Sc_{L_1}^b(t) \cdot \cos(m) + C_{L_1}^A(t) \cdot C_{L_1}^B(t) \cdot C_{L_1}^C(t) \cdot Sc_{L_1}^a(t) \cdot \sin(m) \right] \times \sin(2\pi \cdot F_{L_1} \cdot t),$$

where $C_x^y(t)$ is the ranging code on the y channel of the x carrier frequency; $D_x^y(t)$ is the data signal on the y channel in the x frequency band; $Sc_x^y(t)$ is the rectangular sub-carrier on the y channel in the x frequency band; $F_x$ is the carrier frequency in the x frequency band, and m is the modulation index, associated to the modified hexaphase (interplex) modulation.
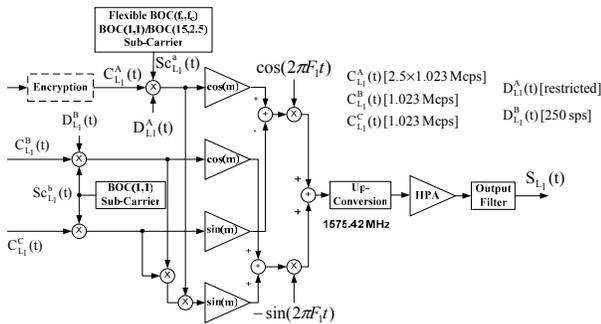


**Figure 9:** E2-L1-E1 signal modulation scheme – modified hexaphase modulation

In order to be consistent with the relative powers required between the three channels, a value of m=0.6155 has been chosen for the modulation index.

In the simulator BOC(1,1) and BOC (15,2.5) have been considered (see Figure 9).

### 4.4.3. Galileo E5 (E5a-E5b) Signal Generator

The Galileo system will transmit four different signals in the E5 band, ranging from 1164.45 MHz to 1214 MHz (see Section 3.2). Two of them will contain navigation messages, while the other two are data-free pilot channels.

The modulation of E5 will be done according to one of the following schemes [HEI02]: 2 QPSK(10) or AltBOC(15,10). Implementation analysis and performance comparisons between the AltBOC(15,10) and the two QPSK of 10 Mcps signals are in progress [ISS03].

The AltBOC(15,10) with constant envelope has been considered in the SDSS simulator, but the 2-QPSK approach may be easily implemented due to the flexibility of the simulator.

**1) 2 QPSK(10).** Two QPSK(10) signals would be generated and transmitted through two separate channels on E5a and E5b respectively (see Figure 10 [HEI02]). Each (I,Q) pair will be modulated on the appropriated center frequency through two independent QPSK modulators. The two separate E5a and E5b signals will be amplified separately and combined in RF before transmission at the 1176.45 MHz and 1207.14 MHz respective carrier frequencies.

The 2 QPSK E5 signal can be written as follows:

$$S_{E5}(t) = \left[ C_{E5a}^I(t) \cdot D_{E5a}^I(t) \times \cos(2\pi \cdot F_{E5a} \cdot t) - C_{E5a}^Q(t) \times \sin(2\pi \cdot F_{E5a} \cdot t) \right]$$
$$+ \left[ C_{E5b}^I(t) \cdot D_{E5b}^I(t) \times \cos(2\pi \cdot F_{E5b} \cdot t) - C_{E5b}^Q(t) \times \sin(2\pi \cdot F_{E5b} \cdot t) \right]$$
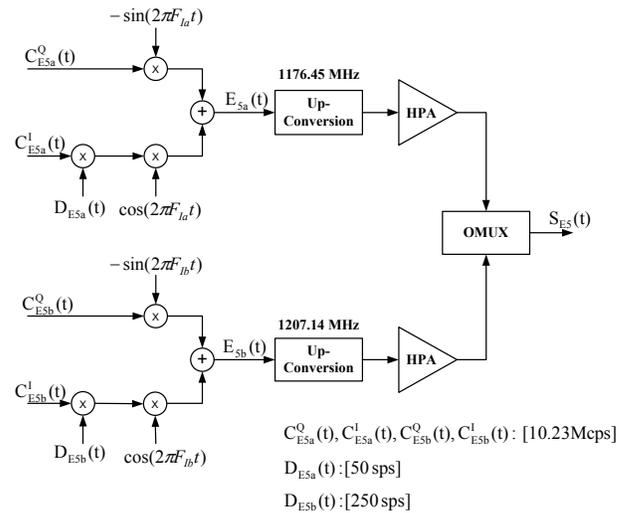


**Figure 10:** E5 signal modulation scheme – 2 QPSK(10)

**2) AltBOC(15,10).** Several approaches to generate the E5a/E5b signals are possible, most of them providing non-constant envelopes. A more suitable approach would be to generate a constant envelope signal: AltBOC with constant envelope or 8-PSK-AltBOC [RIE02a, ISS03].

The signal is then amplified through a very wideband amplifier before transmission at the 1191.795 MHz carrier frequency (see Figure 11). The AltBOC(15,10) modulation combines the two E5a and E5b signals in a composite constant envelope signal.
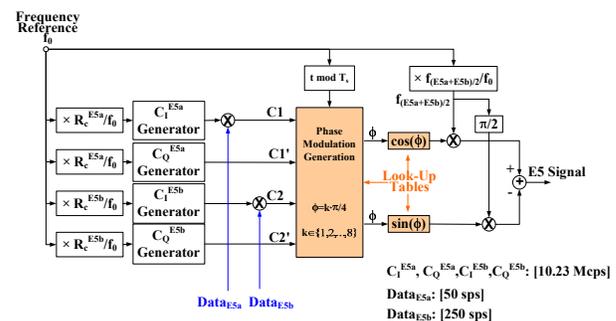


**Figure 11:** E5 signal modulation scheme – AltBOC(15,10)

Defining E5a and E5b spreading codes as C1, C1', C2 and C2', the baseband expression of an AltBOC signal can be expressed as follows [RIE02a, ISS03]:

$$x(t) = [c_1(t) + j \cdot c_1'(t)] \cdot er(t) + [c_2(t) + j \cdot c_2'(t)] \cdot er^*(t),$$

where er(t) = cr(t) + j·sr(t) is a complex square sub-carrier of frequency $f_s$, where cr(t) = sign[cos(2πf_st)] and sr(t) = sign[sin(2πf_st)].

The resulting signal, called AltBOC(15,10), does not feature a constant envelope. It is possible to modify the signal in order to make the envelope constant [ISS03].

The modulation has a constant envelope and presents a 8-PSK constellation: the signal is therefore called "8-PSK AltBOC" rather than "AltBOC with constant envelope".

This modulation scheme can be easily implemented using simple look-up tables for the phase assignments [ISS03]. For more information on the Galileo E5 signal properties see also [BAS04].

In order to summarize the different Galileo signals which have been implemented in the SDSS simulator, the various frequency bands as well as the types of modulation of the various Galileo signals are presented in Table 4.

| Frequency Bands | Channel | Modulation Type | Chipping Rate [Mcps] | Symbol Rate [sps] |
|---|---|---|---|---|
| E5a | I | AltBOC(15,10) | 10.23 | 50 |
| E5a | Q | AltBOC(15,10) | 10.23 | N/A |
| E5b | I | AltBOC(15,10) | 10.23 | 250 |
| E5b | Q | AltBOC(15,10) | 10.23 | N/A |
| E2-L1-E1 | A | $BOC(f_s,f_c)$ $BOC(15,2.5)$ | $m \times 1.023$ $15 \times 1.023$ | TBD |
| E2-L1-E1 | B | BOC(1,1) | 1.023 | 250 |
| E2-L1-E1 | C | BOC(1,1) | 1.023 | N/A |

**Table 4:** Main Galileo navigation signal parameters

Because the future Galileo codes are not available yet, GPS L1 C/A and GPS L5 codes have been used for the Galileo L1 and E5 signals, respectively. The very flexible architecture of the simulator will allow a fast and easy updating for the latest Galileo codes, when available.

### 4.5. PROPAGATION AND DISTURBANCE CHANNEL

The disturbance channel includes thermal noise, tropospheric and ionospheric models, multipath simulation as well as various interference signals (e.g. CWI, PWI, swept CWI, amplitude and frequency modulated signals).

#### 4.5.1. Ionospheric Error Model

The ionosphere is an important source of errors for the GNSS users. The range errors of the ionosphere and troposphere are quite comparable, but the ionosphere is more difficult to model and it varies more than the troposphere [PAR96].

The Klobuchar ionospheric model [KAP96] is considered for the time being in the simulator, other ionosphere models being currently under consideration.

The ionosphere affects the GNSS signals in different aspects, such as: (1) absolute range errors; (2) relative range errors; (3) range-rate errors; (4) refractions; (5) distorsions; (6) amplitude fading and scintillations; (7) phase scintillations. The increase of the satellites elevation results in smaller ionospheric delays.

#### 4.5.2. Tropospheric Error Model

There are several effects that the troposphere may have on the GNSS signals: (1) attenuation; (2) scintillation; (3) delay. The Hopfield tropospheric model is considered in the simulator for the time being, other troposphere models being currently under consideration).

#### 4.5.3. Satellite Clock Errors

This is due to the fact that, despite the very good precision of the on-board satellite clocks, they may drift. Although they are monitored by Earth stations, some residues still remain. The satellite clock error can be computed as:

$$dT_{clck} = a_{f0} + a_{f1} \cdot (T_{tr} - T_{oc}) + a_{f2} \cdot (T_{tr} - T_{oc})^2 + F \cdot ec \cdot \sqrt{A} \cdot \sin E - T_{gd},$$

where $dT_{clck}$ is SV clock correction [s], $T_{tr}$ the time of transmission [s], F=-4.442807633·10$^{-10}$ [s/m$^{1/2}$], ec the SV orbit eccentricity [unity], A the SV orbit semi major axis [m$^{1/2}$], E the SV orbit eccentric anomaly [rad] or [deg] and $a_{f0}$, $a_{f1}$, $a_{f2}$ are parameters from the broadcast ephemeris.

The power level of the GNSS signal received by a receiver is function of the elevation of the corresponding satellite. For example, the GPS system has been designed to have the highest received signal power for elevations of 45 deg [KAP96]. The same behavior has been assumed for the Galileo signals, as no information has been provided so far.

#### 4.5.4. Multipath

The multipath implemented in the simulator may be added on any GNSS signal. A maximum of three multipath signals may be considered for a given satellite. The multipath has been considered as a signal with a lower power and a delay compared to the direct signal.

Several studies on the multipath characterization in various environments have been presented in the literature. They emphasize that the multipath in the signal propagation channel, when using a spread spectrum technique, may be divided in near and far echoes [JUL04].

### 4.6. INTERFERENCE SIGNALS

Several types of interference have been considered in the simulator, such as Carrier Wave Interference (CWI), Pulsed Wave Interference (PWI), Swept CWI, Amplitude Modulated Interference (AM) and Frequency Modulated Interference (FM). The user has the possibility to define the Jammer-to-Noise Ratio (JNR) for each interference signal, as well as their corresponding frequency parameters and the period when they should operate.

### 5. SDSS SIMULATION RESULTS

Currently, as the generation of the GNSS signals is not completely implemented and validated in the FPGA, the various IF signals are generated on a PC. Hence, the IF SDSS simulator results presented in this section have been obtained in simulation.

## 5.1. GPS L1 C/A SIGNAL

The Power Spectral Density (PSD) of the IF GPS L1 C/A signal is presented in Figure 12, where a sampling frequency $F_s = 10$ MHz has been considered.
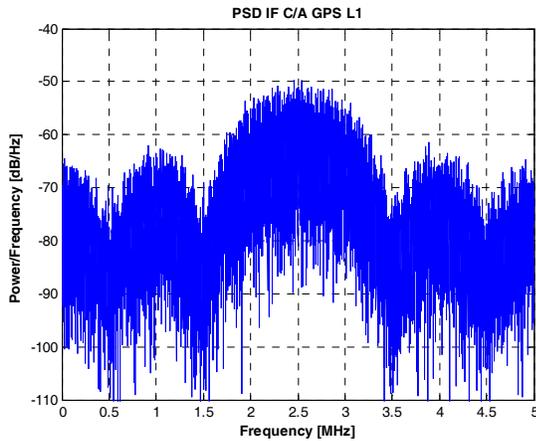
**Figure 12:** PSD of the IF GPS L1 C/A signal

The GPS L1 C/A signal implementation has been validated from the PSD point of view and by comparing the first 10 bits of the C/A for all PRN values with the theoretical ones, which may be found, for example, in [KAP96].

## 5.2. GPS L5 SIGNAL

The PSD of the baseband in-phase GPS L5 signal (I5) is presented in Figure 13, while the PSD corresponding to the baseband I5 with the NH(10) code is presented in Figure 14. The results obtained for the corresponding quadrature-phase signals, Q5 and Q5 with NH(20) are similar and they are not presented in the paper. The PSD of the resulting IF GPS L5 signal is presented in Figure 15, where $F_s = 80$ MHz.
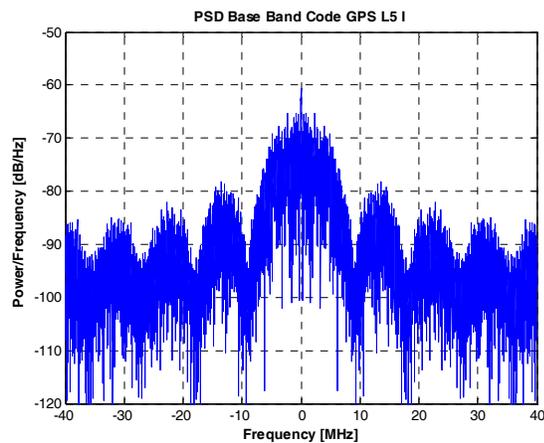
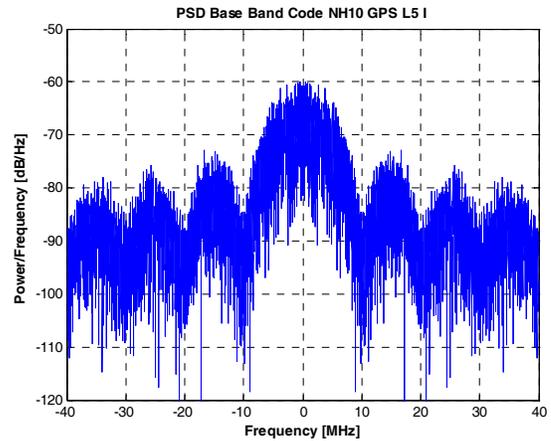**Figure 13:** PSD of the baseband GPS I5 signal

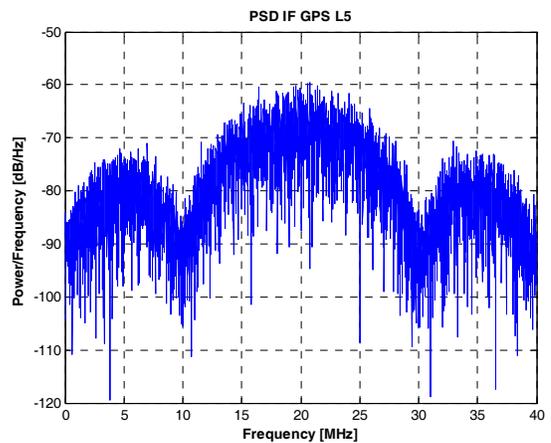**Figure 14:** PSD of the baseband GPS I5 with NH(10) signal

**Figure 15:** PSD of the IF GPS L5 signal

The validation of the GPS L5 signal implementation has been done from the PSD point of view and by comparing the first 13 bits of the I and Q codes (XI and XQ from Figure 8) for all PRN values with the theoretical ones, which may be found in [ICD01].

## 5.3. GALILEO L1 SIGNAL – BOC(1,1)/BOC(15,2.5)

In the case of the Galileo L1 signal containing 2 BOC(1,1) and 1 BOC(15,2.5) signals, the PSDs of the baseband Galileo L1 BOC(1,1), BOC(15,2.5) signals and of the resulting modified hexaphase modulated Galileo L1 signal are presented in Figure 16 , Figure 17 and Figure 18, respectively, where $F_s = 70$ MHz.
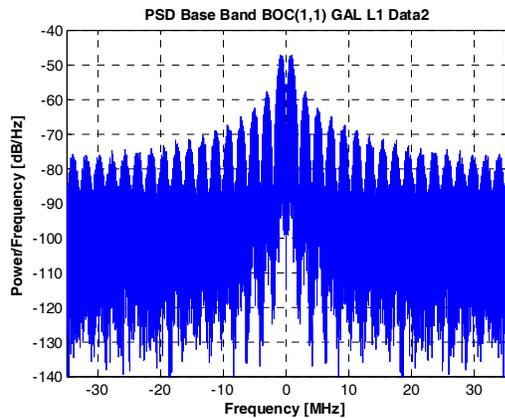
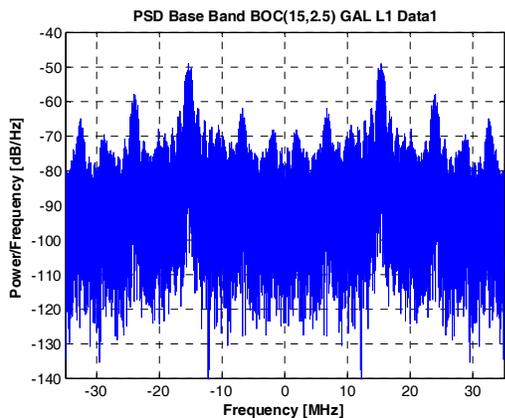**Figure 16:** PSD of the baseband Galileo L1 BOC(1,1) signal



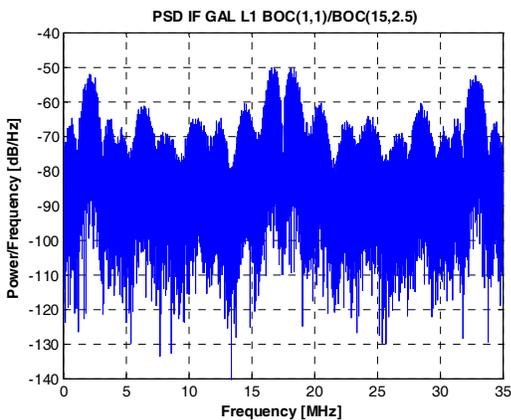**Figure 17:** PSD of the baseband Galileo L1 BOC(15,2.5) signal



**Figure 18:** PSD of the IF Galileo L1 signal

Note that as the signal simulator architecture is very flexible, the BOC(1,1) and BOC(15,2.5) signals may be easily replaced for various tests.

### 5.4. GALILEO E5 – ALTBOC SIGNAL

For the generation of the Galileo E5 signal, the AltBOC(15,10) signal with constant envelope has been considered [ISS03, KRE04]. The PSD of the IF Galileo E5 signal is presented in Figure 19, where $F_s = 240 \times 1.023$ MHz.
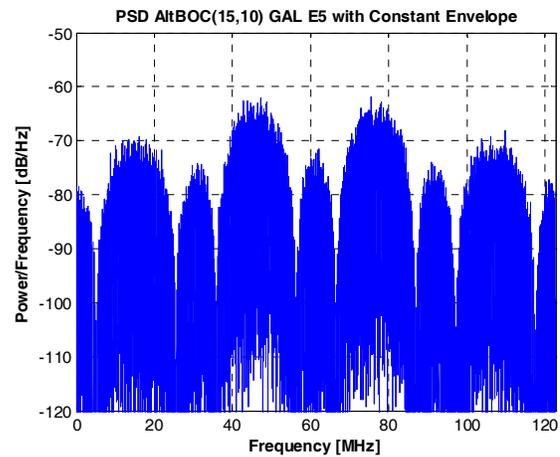


**Figure 19:** PSD of the Galileo E5 – AltBOC(15,10) signal with constant envelope

### 6. CONCLUSIONS

This paper describes a hybrid IF Software Define Signal Simulator (SDSS). The simulator consists in 5 main parts: GNSS satellite constellations generation, receiver trajectory generation, hybrid signals generation, disturbance and propagation channel, as well as interference signals. The main part of the paper presents the IF SDSS simulator, its functionalities and implementation, as well as the modulation schemes for the various signals considered: GPS L1 and L5, Galileo E2-L1-E1, E5a/E5b.

Power spectral density results have been presented for the signals implemented in the simulator. The GPS L1 and L5 signals have been also validated by comparing the code values to the theoretical ones.

As the parameters of the future Galileo signals are not yet completely defined, updates will be brought to the simulator in order to keep it as realistic as possible. For example, new information recently published in [ICD05] will be taken into account in the near future. Also, the Galileo E5 AltBOC(15,10) signal will be better analyzed and validated.

Future work concerns the validation of the GPS L1 navigation message, the implementation of the GPS L5 one and the implementation analysis of several ionospheric and tropospheric models.

The most complex test, which represents the best way in testing a signal generator, is to connect it to a real receiver.

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