GNSS Bit-True Signal Simulator
A Test Bed for Receivers and Applications

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Abstract. This work aims to provide the status and the outcomes of the GNSS Bit-True Signal Simulator (GBTSS) software that is developed, and now it is under completion and optimization, in the Navigation & Integrated Communications Business Unit of Alcatel Alenia Space Italia. This simulator provides the I & Q samples of any GNSS signal as seen at the correlators input of a GNSS receiver.

1 Needs and Applications

Currently the Galileo Navigation System development is on-going under an ESA/GJU contract but the Galileo Signal-In-Space (SIS), although the launch of the experimental GIOVE Satellites, is not yet completely frozen (see also the studies on a Modified BOC modulation proposed by the US/EU SIS working group 0). In parallel to these system engineering activities, several applications are under study and prototyping involving different types of receivers. These two aspects, system engineering activities and receivers design, are strictly correlated by their common physical link: the Navigation Signal.

From the system engineering point of view, the interest on the navigation signal is focused on its performance analysis, on its possible evolutions, on the interoperability with GPS and on its co-existence with other signals in the same bands (i.e. Radars, DME, etc. . .).

From the receivers design point of view, the interest is on the applications in their different domains that drive the receiver architecture also in terms of received signals and bands.

In order to overcome this needs coming from both system engineering and receiver design, it is necessary to have a flexible and configurable facility able to generate any type of navigation signal.

In this paper it is presented a possible solution to meet these needs.

In particular in the following section will be presented a GNSS signal simulator named GBTSS (GNSS Bit-True Signal Simulator) under development at the B.U. Navigation and Integrated Comms of the Alcatel Alenia Space Italia S.p.A. The GBTSS is a facility conceived to generate the I & Q samples of any kind of Navigation Signal; in fact the tool guarantees the flexibility and the configurability so as to give at any user the possibility to reproduce the required GNSS signal.

The architectural design and the current GBTSS status will be described; in the last section, simulation results and the way forward of this project will be provided.

2 System Architecture

Starting from the needs, it is clear that the main functionality of the GBTSS is to be able to generate any type of Navigation taking into account all the effects impacting the signal path from the satellite to the ADC output of the receiver. In order to do that, the architectural choice is of fundamental importance. The solution chosen, after several analyses and trade-off, is to digitally reconstruct the signal path starting from the A/D Converter output (e.g. taking into account a configurable sampling rate) and introducing all the effects from the local errors (i.e. receiver noise, multipath and interference) up to the satellite-user relative (e.g. Doppler).

Figure 1 provides a flow description of the GBTSS Simulated Signal.

How it can be noted from the figure, the simulator is composed of three main blocks:

- the Signal Generator block
- the Environment block
- the Receiver and Local Error block

The **Signal Generator block** is composed by:

- *Satellite* module, that contains all the information about the satellite. In particular, using an Orbit propagation module, the satellite position and velocity are computed.
- *User Receiver* module, that computes the receiver position and velocity, using an Orbit propagator.
- *Kinematics* module, that provides the Doppler components taking into account the satellite and the receiver position and velocity.
- *Signal in Space* module. Inputs to this block are the Doppler components and all the signal characteristics (like the transmitted bandwidth or the carrier frequency) and the output is the generation of the selected signal in time domain.

The **Environment block** is composed by:

- *Elevation and Azimuth* module, that provides the satellite elevation angle and azimuth taking into account the satellite and the final user position and velocity information.
- *Ionosphere* module, that provides the signal delay and the phase variation on the satellite elevation angle and azimuth information.
- *Troposphere* module. This block provides the signal attenuation and delay on the satellite elevation angle and azimuth information.
- *Free Space Propagation* module. This block computes the signal propagation time between the satellite and the receiver.

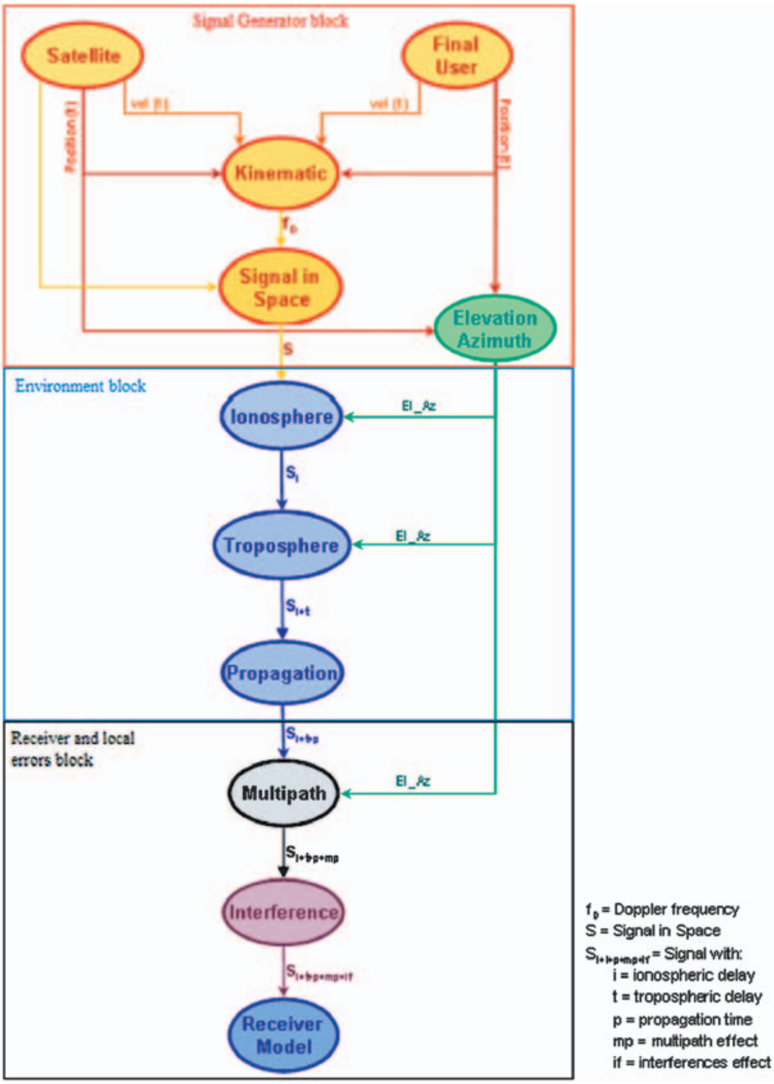

Fig. 1. GNSS signal state flow.

The **Receiver and Local Error block** is composed by:

- *Multipath* module, starting from the signal affected by the environmental effects previously described and the satellite elevation angle and azimuth information, adds to the "real" signal the multipath signal.
- *Interference* module, it represents the possible impact of the external signal to the receiver, like the L-band primary radar signals.

- *User Receiver* module, it adds to the signal, the Gaussian noise created as a random vector of numbers with variance equal to σ. The vector composed by two rows, one for the in-phase component and another one for the quadrature. Since the two components are generated separated to guarantee that both I and Q channels will be statistically independent. Noise is thus added separately for the in-phase and quadrature channels of the received signal. Plus, the *User Receiver* module is able to implement any possible impact of the receiver model, from the antenna input to the A/D Converter level.

2.1 GBTSS Implementation

The GBTSS software aims to simulate any signal type and its navigation path from the satellite to the user receiver and provides the I & Q samples of any Navigation signal at the correlators input of a GNSS receiver.

In order to simulate any signal type, the GBTSS will implement all the modulation schemes and in particular the following Galileo modulations, in addition to the GPS BPSK one, are foreseen:

- The CEM modulation (Coherent Envelope Modulation) modulates the central frequency so to create 3 channels: A, B, and C that operate at the same signal central frequency.
- The BOC(f_S,f_C) modulation (Binary Offset Carrier) (f_S is the subcarrier frequency and f_C is the code frequency) modulates the signal with a rectangular sub-carrier [2]:

$$S(t) = s(t) \cdot sign(\cos(2\pi \cdot f_s \cdot t)) \quad (0)$$

- The AltBOC(f_S,f_C) modulation modulates the signal with a complex rectangular sub-carrier [2]:

$$S(t) = s(t) \cdot sign(\cos(2\pi \cdot f_S \cdot t) + j \cdot \sin(2\pi \cdot f_S \cdot t)) \quad (1)$$

- The BPSK modulation (Binary Phase Shift Keying), that is a particular case of M-PSK modulation with two level (M = 2).

As previous described, the ideal signal is generated by the Signal Generator block in the time domain and passed throw to the Environment block that provides to add the environmental errors.

The *Free Space module* simulates the delay due to free space of a signal transmitted from a satellite to a receiver, that include the corrections for the relativistic Sagnac and Orbit Eccentricity effects.

The *Ionospheric module*, implements the delay due to the free electrons and positively charged ions produced by the solar radiation, Δt_{iono} also called Ionospheric Slant Delay Δs that is a function of the Total Electron Content (TEC).

The GBTSS implements the NeQuick model for the TEC determination that is the model used by the Galileo system.

The NeQuick model is an ionospheric electron density model able to give the electron concentration distribution on both the bottom side and topside of the ionosphere and it is a quick-run model particularly tailored for trans-ionospheric applications.

To guarantee a major flexibility and usability of the GBTSS for both the Galileo and the GPS system, the simulator also implements the Klobuchar model, that is used for the GPS ionospheric effect calculation.

The Klobuchar ionospheric model uses a half cosine to represent the diurnal variation of TEC in the single-frequency user algorithm.

Another deviation from the vacuum speed of light is caused by the *Troposphere*. Variations in temperature, pressure and humidity contribute to the variations of the speed of light and consequently of the radio waves. The total troposheric delay is given by:

$$\Delta t_{totalTropo} = \Delta t_{dryTropo}\, m_{dry}(E) + \Delta t_{wetTropo}\, m_{wet}(E) + (\Delta t_{noise} + \sigma_{noise} \bullet RAN) \qquad (2)$$

where $\Delta t_{dryTropo}$, $\Delta t_{wetTropo}$ are the Dry and Wet Tropospheric Zenith Delays [s] and

$$m_{dry}(E) = \frac{1}{\sin\sqrt{E^2 + 6.25}} \quad \text{and} \quad m_{wet}(E) = \frac{1}{\sin\sqrt{E^2 + 2.25}} \qquad (3)$$

are the dry and wet delay Mapping Functions for an Elevation Angle E [rad]. The Noise Mean Deviation Δt_{noise} and the Noise Standard Deviation σ_{noise} represent the nominal tropospheric noise parameters that are meant to represent errors due to uncertainty in meteorological situations. These parameters may be overwritten by user-settable Feared-Event values when the tropospheric Feared Event is activated. The random number RAN is a time-correlated Gaussian function [3].

In literature, there are several model to calculate the tropospheric effects:

- Saastamoinen Total Delay Model
- Hopfield Two Quartic Model
- Black and Eisner (B&E) Model
- Water Vapor Zenith Delay Model – Berman
- Davis, Chao, and Marini Mapping Functions
- Altshuler and Kalaghan Delay Model

Both GPS and Galileo system use the Saastamoinen model for the Tropospheric correction.

In the Saastamoinen model, the dry pressure is modelled using the constant lapse rate model for the troposphere and an isothermal model above the tropopause. The vertical gradient of temperature is $T = T_0 + \beta(r - r_0)$, and the resulting pressure profile is $P = P_0\left(T/T_0\right)^{\frac{-Mg}{R\beta}}$ where r is the radius from the Earth centre $\left(r = (R_e + h)\right)$ and r_0 is the user radius (usually $r_0 = R_e$, the Earth radius), and T_0 is the user temperature. The radius r ranges in value from r_0 to r_T which represents the radius to the tropopause. The corresponding dry refractivity is then $n - 1 = (n_0 - 1)\left(T/T_0\right)^{\mu}$ where $\mu = -M/R\beta - 1$ is a constant exponent. Using an isothermal model above the tropopause, the pressure drops exponentially from its initial value at the tropopause P_T:

$$P = P_T \exp\left[-\frac{gM}{RT_T}(h - h_T)\right] \qquad (4)$$

where the subscript T refers to the values at the tropopause.

The wet refraction is dependent on the partial pressure e, which decreases in somewhat the same way as total pressure in the troposphere although much more rapidly.

The Saastamoinen model provide, for elevation angles $E \geq 10$ deg, a delay correction:

$$\Delta = 0.002277\,(1+D)\sec\left(\psi_0\left[P_0 + \left(\frac{1255}{T_0} + 0.005\right)e_0 - B\tan^2\psi_0\right]\right) + \delta_R \qquad (5)$$

where Δ is the delay correction in meters; P_0, e_0 are in millibars and T_0 is in °K. The correction terms B and δ_R are given in Table 1 for various user heights h. The apparent zenith angle ψ_0 = 90 deg – E. The value of D is D = 0.0026 cos 2ϕ + 0.00028h, where ϕ is the local latitude and h is the station height in km [4].

The *Total Environment block* takes in input:

- The signal in space;
- The satellite elevation angle and azimuth information;
- The final user elevation angle and azimuth information;

and calculates the Total Environment Delay of the signal, from its time of emission to time of reception, by summing the Free Space Delay, the Ionospheric Delay and the Tropospheric Delay for each broadcast frequency.

The Total Environment Delay is defined as:

$$\Delta t_{totalEnv} = \Delta t_{freeSpace} + \Delta t_{iono} + \Delta t_{totalTropo} \qquad (6)$$

After this phase, the software passes the delayed signal to the *Receiver and Local Error Block* that adds to the signal the local and the user receiver chain errors (multipath, interferences, etc.).

Table 1. Correction terms for saastamoinen model.

	Apparent Zenith	Station height above sea level							
	Angle	0 km	0.5 km	1 km	1.5 km	2 km	3 km	4 km	5 km
	60 deg 00 min	0.003	0.003	0.002	0.002	0.002	0.002	0.001	0.001
	66 deg 00 min	0.006	0.006	0.005	0.005	0.004	0.003	0.003	0.002
	70 deg 00 min	0.012	0.011	0.010	0.009	0.008	0.006	0.005	0.004
	73 deg 00 min	0.020	0.018	0.017	0.015	0.013	0.011	0.009	0.007
	75 deg 00 min	0.031	0.028	0.025	0.023	0.021	0.017	0.014	0.011
	76 deg 00 min	0.039	0.035	0.032	0.029	0.026	0.021	0.017	0.014
δ_R	77 deg 00 min	0.050	0.045	0.041	0.037	0.033	0.027	0.022	0.018
	78 deg 00 min	0.065	0.059	0.054	0.049	0.044	0.036	0.030	0.024
	78 deg 30 min	0.075	0.068	0.062	0.056	0.051	0.042	0.034	0.028
	79 deg 00 min	0.087	0.079	0.072	0.065	0.059	0.049	0.040	0.033
	79 deg 30 min	0.102	0.093	0.085	0.077	0.070	0.058	0.047	0.039
	79 deg 45 min	0.111	0.101	0.092	0.083	0.076	0.063	0.052	0.043
	80 deg 00 min	0.121	0.110	0.100	0.091	0.083	0.068	0.056	0.047
	B [mbar]	*1.156*	*1.079*	*1.006*	*0.938*	*0.874*	*0.757*	*0.654*	*0.563*

Multipath is the phenomenon whereby a signal arrives at a receiver via multiple paths attributable to reflection and diffraction. Multipath represents the dominant error source in satellite-based precision guidance system.

Multipath distorts the signal modulation and degrades accuracy in conventional and differential systems. Multipath also distorts the phase of the carrier, and hence degrades the accuracy of the interferometric systems. For standard code-based differential system, signal degradation attributable to multipath can be severe. This stems from the fact that multipath is a highly localized phenomenon.

A possible parameterization to simulate the effect of multipath reflections on the measured range, phase and Doppler shift, is follow described. The main input to the algorithm is the transmitter elevation and the main outputs are the multipath range, phase and Doppler errors.

The range error E_{mr} (in meters), phase error E_{mp} (in meters) and Doppler frequency error E_{mf} (in Hz) due to multipath can be computed as follows [3]:

$$E_{mr} = A_{br} + A_r K_{env} K_{rec} K_{ran} \cos(\omega Elev) \tag{7}$$

$$E_{mp} = A_{bp} + A_p K_{env} K_{rec} K_{ran} \cos(\omega Elev) \tag{8}$$

$$E_{mf} = A_{bf} + A_f K_{env} K_{rec} K_{ran} \cos(\omega Elev) \tag{9}$$

where A_r, A_p and A_f are the amplitude of the multipath effect, A_{br}, A_{bp} and A_{bf} are residual multipath bias terms, K_{rec} is the receiver sensitivity factor (0 to 1), ω is the multipath frequency and *Elev* is the elevation angle of the transmitter relative to the receiver.

K_{env} depends on the receiver environment characteristics. Table 2 some of the values that can be used:

K_{ran} is a time-correlated Gaussian distribution noise of mean standard deviation of σ, Correlation time τ and Correlation Enable state.

Through most the above parameters can be user-settable, some representative default values are $A_r = 2\ m$, $A_p = 0.2\ m$, $A_f = 1Hz$, $K_{rec} = 1$, $\omega = 0.8 cycle / \deg ree$. The residual biases is zero by default.

The GBTSS implements this phenomena as described in the previous equations.

The navigation systems, GPS/EGNOS and Galileo, uses the same frequency band of the primary surveillance radar for Air Traffic Control and DME systems so it is possible to have interference effects coming from this radar (Fig. 2).

Table 2. Relations between the kenv values and the environment characteristics.

$K_{env} = 0.0$	None
$K_{env} = 0.1$	Rural
$K_{env} = 0.2$	Fly
$K_{env} = 0.3$	Airport
$K_{env} = 0.4$	Harbour
$K_{env} = 0.5$	Sail
$K_{env} = 0.6$	SubUrban
$K_{env} = 0.7$	Urban
$K_{env} = 0.8$	Excessive

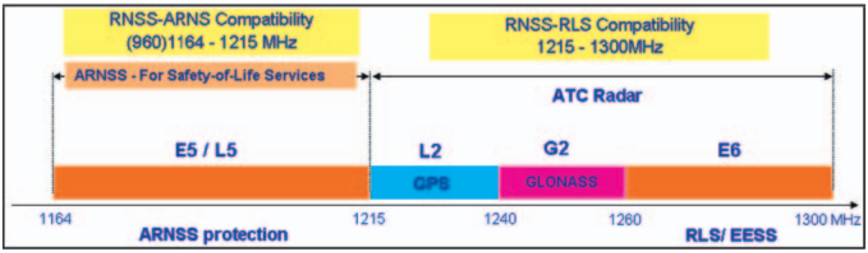

Fig. 2. Allocation frequency.

For example, in Italy, the primary radars that work in L band are the ATCR-44K and the ATCR-44S.

The ATCR 44S is a radar with a solid state power amplifier that employs two coded and different waveforms for the short and long distance coverage.

This radar has two impulse types (Fig. 3):

- short impulse of 32 μs for short distance coverage
- long impulse of 150 μs for long distance coverage

Both impulses are compress at 2.8 μs in order to employ the same receiver chain.

Another possible interference effect can be provided by the DME/TACAN systems.

DME and TACAN are pulse-ranging navigation systems that operate in the 960-1215 MHz frequency band. DME systems provide distance measurement for aircraft; TACAN, a military navigation system, provides both azimuth and distance information. DMEs and TACAN operate in four modes (X, Y, W, Z) as shown in Fig. 4. The DME/TACAN navigation system comprises airborne interrogators and ground-based transponders. The interrogators on board aircraft transmits pulse pairs on one of 126 frequencies with 1 MHz spacing. The ground transponders are usually able to transmit up to 2700 pulses pairs per second (ppps) for DME and 3600 ppps for TACAN, though some DME transponders are capable of transmitting 5400 ppps. However, in normal operation, these rates are only encountered in peak traffic situations.

The DME and TACAN systems operate by transmission from the aircraft of a pair of pulses on the nominal frequency of a visible ground-based transponder, with nominal duration 3.5 microseconds separated by 12 microseconds, as shown in Fig. 5.

The ground-based transponder receives, frequency converts and re-transmits these pulse pairs towards the aircraft receiver, which is able to measurement the delay between transmission and reception and hence calculate the distance to the DME transponder [5].

In the GBTSS the *Interference module* these and other similar effects are modelled.

At the Receiver Level, the signal is down-converted to an intermediate frequency and, after the A/D conversion and the filtering process, it is possible to compute the I & Q samples.

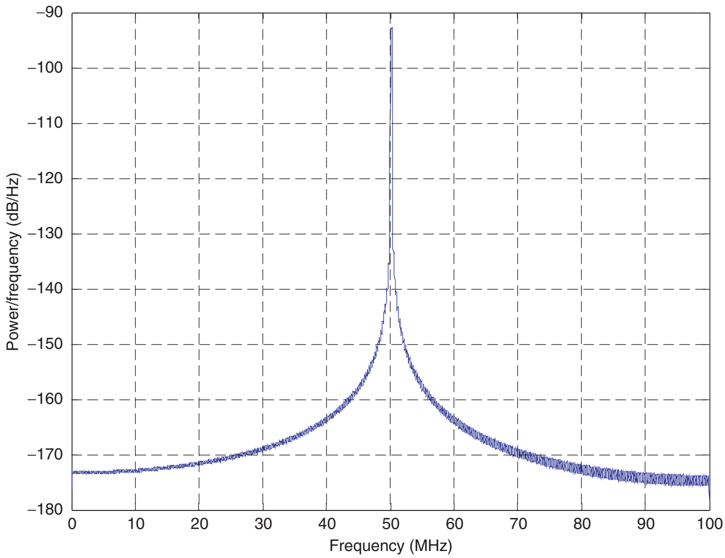

Fig. 3. Long pulse PSD.

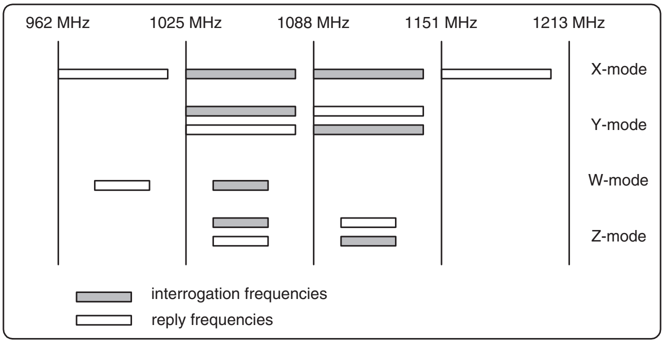

Fig. 4. Standard DME/TACAN channel plain.

The *User Receiver module* contains a Generic Receiver front-end model which receives the GNSS signals from the visible satellites and computes the observables.

Range measurements are simulated by adding measurement errors to the range information provided by the Environment model. These measurement errors are function of noise and multipath effects.

Phase measurements, corrupted by error terms like the clock drift rate and noise, are simulated by integrating the Doppler frequency.

The clocks are modelled as a specific offset relative to the reference time of the segment containing the clock. The reference times are: International Atomic Time, Universal Time Coordinated, Galileo System Time or GPS Time.

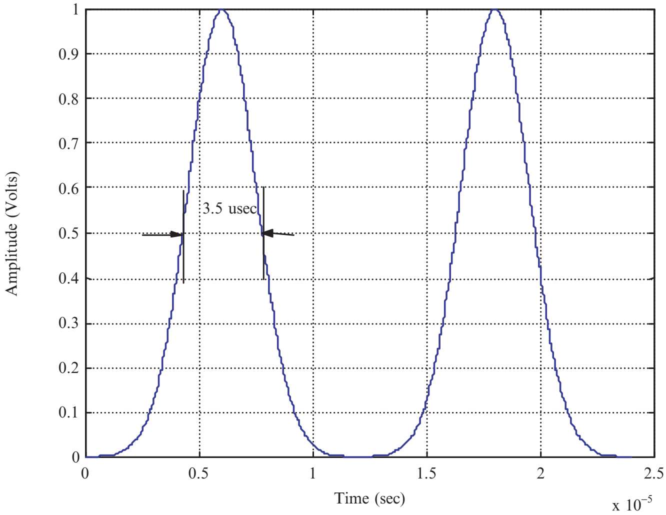

Fig. 5. Ideal gaussian DME pulse-pair.

The clock offset includes:

- Systematic clock error (bias, drift and acceleration)
- Clock drift correction commands
- Thermal noise errors
- Severe drift (feared event)

There are generally five sources of clock noises that can be presented:

- Random walk on frequency
- White noise on frequency
- Flicker noise on frequency
- White noise on phase
- Flicker noise on phase

Random walk is the integration of white noise. It is time-correlated and generates a decreasing power spectral density proportional to 1/f (f is the frequency).

White noise is typically a time independent random sequence with Gaussian distribution. It generates a constant power spectral density (same energy at all frequency, therefore "white").

Flicker noise is a time correlated random sequence also generating a decreasing power spectral density proportional to 1/f (less so than for random walk). More energy at the low frequencies gives more prominent slow varying effects and less prominent fast changing effects [3].

The clock offset error is defined as:

$$\Delta t_{clockDrift} = \Delta t_{clockDrift,\, rx} - \Delta t_{clockDrift,\, sv} \quad (10)$$

where

$\Delta t_{clockDrift,\, rx}$ is the Receiver Clock Drift Error [s]

$\Delta t_{clockDrift,\, sv}$ is the Spacecraft Vehicle Clock Drift Error [s] .

3 GBTSS Vallidation Status

Each block, previously described, it will be separately validated.

At the moment it has been implemented the *Signal in Space* block, without considering the Doppler components, and the *Environment* block. This blocks have been implemented in Matlab language and then translated in C language. Particularly it has been simulated the three bands of the Galileo signals: E5 (1191.795 MHz), E6 (1278.750 MHz), L1 (1575.420 MHz).

The Galileo E5 signal is modulated in accordance to the AltBOC(10,15) modulation scheme as reported in Fig. 6:

The AltBOC signal constellation and the baseband power spectral density are showed in Fig. 6.

Other simulation results are showed in the Fig. 7. In particular, the outcomes of Constant Envelope Modulation (CEM) scheme, used in the Galileo E6 signal, is plotted at the constellation level, in Fig. 7a, and at the Power Spectral Level, in Fig. 7b.

The CEM scheme uses a suitable input channel combination in order to have an constant output power level, in particular for the chosen multiplexing scheme (CEM) the constant envelope is maintained by adding to the desired channels A, B and C an additional signal, which is the product of all desired binary signals.

The CEM scheme is also employed in the Galileo L1 signal, the only difference, between L1 and E6, lies in the channel input combination. An BOC(1,1) modulation scheme is used in the L1 Galileo signal for both the A, B CEM channel inputs. The GBTSS output is reported in Fig. 8.

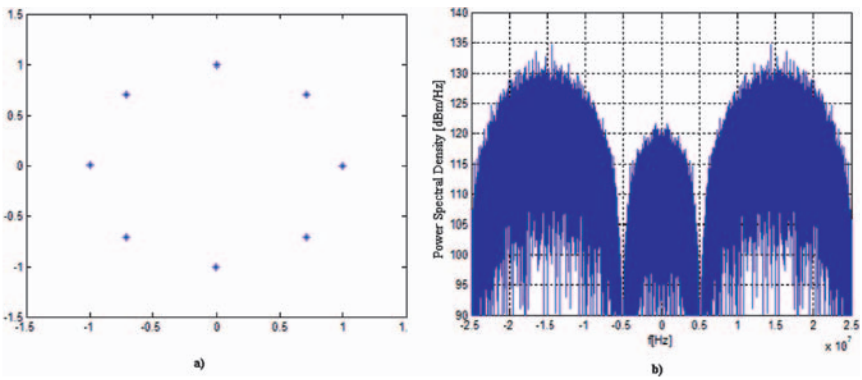

Fig. 6. a) Galileo E5 AltBOC signal constellation; b) Galileo E5 power spectral density.

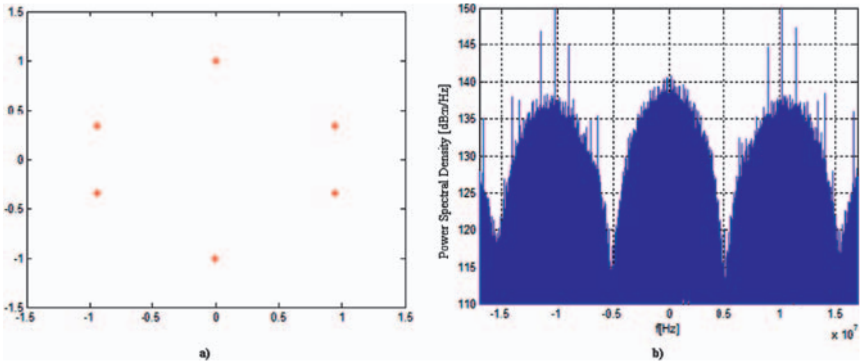

Fig. 7. a) Galileo E6 signal constellation; b) Galileo E6 Power spectral density.

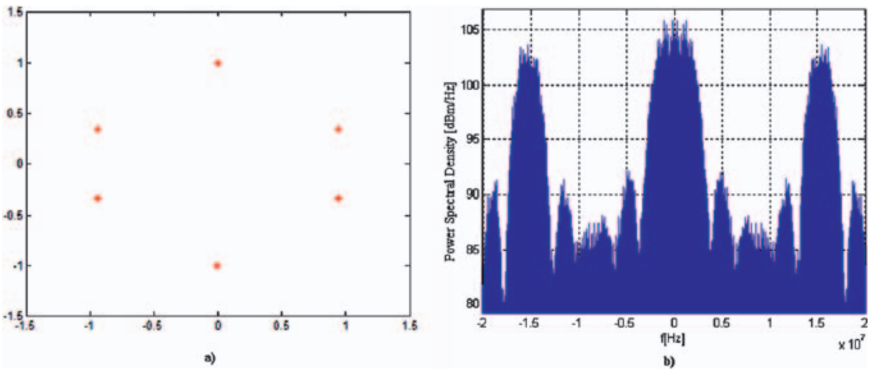

Fig. 8. a) Galileo L1 signal constellation; b) Galileo L1 power spectral density.

The described signals are sent from the satellite to the user receiver through the atmospheric that induces environmental effects (i.e.: delay) on the signals; in particular in this phase is utilized the Klobuchar model for the ionospheric effects and the Saastamoinen for the tropospheric ones.

In the Table 3 are reported the generation parameters utilized to compute the delay introduced in the satellite channel; in particular in Fig. 9 can be noted the delay effects on the sub-carrier of the BOC Galileo E6 signal. The corresponding delay values are:

- Ionospheric delay ≅ 0.05 μs (corresponding to an error of about 15 m);
- Tropospheric delay ≅ 0.02 μs (corresponding to an error of about 7 m);
- Propagation delay ≅ 0.09 s.

Table 3. Inputs value for atmosphere effects determination.

Receiver geodetic latitude [deg]	41
Receiver geodetic longitude [deg]	12
Satellite geodetic azimuth [deg]	210
Year	2006
Month	2
Day	1
Hour	9
Minuts	35
Seconds	0
Satellite elevation angle [deg]	20

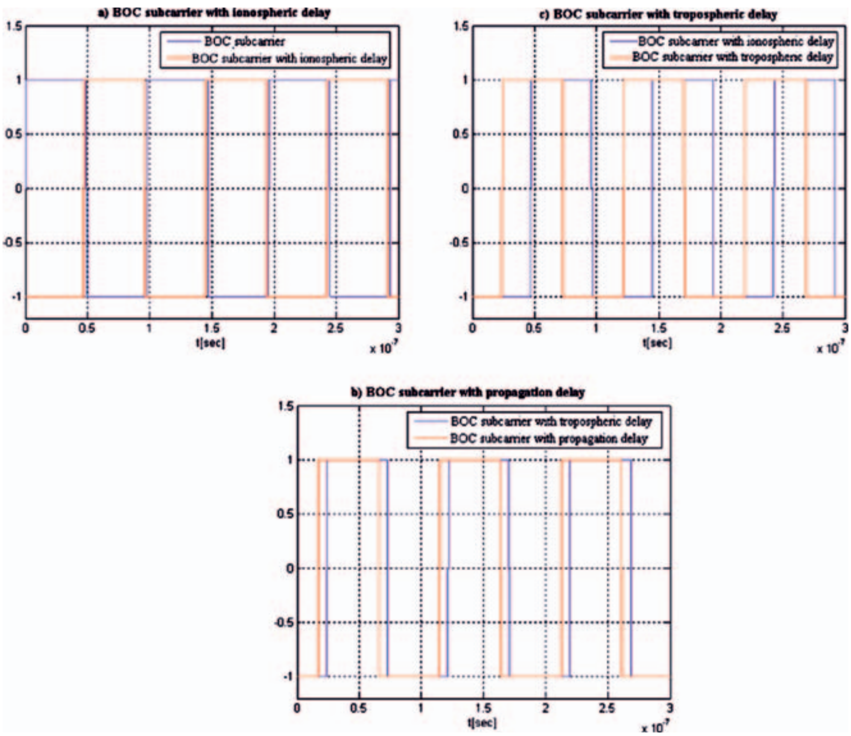

Fig. 9. a) E6 BOC subcarrier with ionospheric delay; b) E6 BOC subcarrier with tropospheric delay; c) E6 BOC subcarrier with propagation delay.

In this section of the paper has been reported the main simulation results; the authors would inform that the whole signals simulator parameters was been implemented in accordance to the Galileo SIS-ICD [6].

4 Conclusion and Outlooks

In the previous sections, an Alcatel Alenia Space Italia GNSS signal simulator architectural design was presented. How it can be noted, the GBTSS is not yet fully developed, for this reason in the paper it was be presented only the main results related to the developed parts.

Currently multipath, interference and receiver error modules are under development, besides new modules that generates the atmospheric effect are in the testing and verification phase.

As previously described the main idea is to realize a GNSS signal simulator able to generate any kind of GNSS signal under any transmission scenario. To reach this goal the GBTSS will be realized like a framework that can contain and drive different modules, an opportune combination of these modules will cover any kind of scenarios.

The future ideas are to fully develop the simulator so to apply it to the B.U. R&D and programmatic activities. In particular, The GBTSS will be employed in the frame of Galileo System Integration and Verification activities, Receivers development, Signal characterization and for all the R&D activities that involve the navigation signals.

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