

Using the GRANADA Bit-True Simulator to analyse the effect of Code Doppler shift in Galileo E5 and L1 Receivers

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ABSTRACT

Among its priorities, the Galileo Joint Undertaking (GJU) is in charge of managing the Research and Development activities related to the Galileo Programme. In the context of the European Commission 6th Framework Programme, GJU has initiated the Galileo Receiver Preliminary Development. Presently the GALILEO Receiver Development Activities (GARDA) project is running at this scope. This paper focuses on the Galileo Receiver ANalysis and Design Application (GRANADA), a new concept of Galileo SW Receiver Simulator, which development is part of the GARDA project [1], [2]. The tool has been developed by Deimos Space under Alenia Spazio specification.

A Software (SW) Receiver is a key element in the GARDA project. GRANADA covers a dual role: test-bench for integration and evaluation of receiver technologies on one side, and SW receiver as asset for GNSS application developers on the other side. GRANADA is conceived as a modular and configurable tool, in which the user can embed and test his/her own algorithms with a user-friendly interface. It runs on a standard Windows PC, allowing the maximum use from people not involved in the development. The application recreates the bit-true signal processing chain of a Galileo receiver. It models the RF front-end, and processes IF measurements, including the correlation and filtering, signal and data processing and PVT computation, allowing the use of GPS combined with Galileo. The receiver architecture is based on GARSIM (Galileo Receiver Simulator), also developed by Deimos and Alenia Spazio, under ESA contract, for the Pre-development of the Galileo Ground Segment Reference Receiver [3].

In this paper, an analysis of the code Doppler shift in Galileo E5 and L1 open service channels using the GRANADA bit-true simulator is presented. Due to both satellite and user dynamics, the incoming Galileo signal is distorted by a Doppler shift that produces an additional error in the pseudorange and carrier phase measurements. Since in any conventional receiver carrier Doppler shift is estimated by the FLL/PLL loops or using additional carrier aided techniques, code frequency shift can be the main error source due to system dynamics.

Taken benefit of GRANADA capabilities, different scenarios have been simulated in order to characterise the impact of the code Doppler shift in the receiver performance. The outputs include the pseudorange error as a function of the relative velocity for the Galileo E5 AltBOC and L1 BOC(1,1) open services channels. The aim of the study is to assess the environmental conditions that require a code aided technique to mitigate the Doppler shift, i. e., the maximum velocity that allows a good reception without removing the code frequency offset, and the expected benefits provided by the aiding.

After presenting the GRANADA simulator, the insertion of code Doppler shift in the transmitted signal is described in detail. This operation is based on applying a variable delay to the generated baseband signal using interpolation techniques. Finally, the results of the exhaustive simulations performed on Galileo E5 and L1 signals are presented and analysed. Recommendations to mitigate this effect as a function of the receiver dynamics are provided.

TOOL DESCRIPTION

GRANADA is a SW suite including two complementary tools that allows the user to perform different analyses, or to investigate specific functions and algorithms of the receiver. The two approaches have also different characteristics of modularity, CPU requirements and COTS licenses.

1. Bit-True GNSS SW Receiver Simulator (Matlab/Simulink).

This tool, developed in Matlab/Simulink to provide high modularity, targets receiver experts in the development and analysis of the so-called "Receiver core technologies". It implements a dual-channel receiver (data and pilot channel) of a specific Galileo carrier. The GRANADA bit-true simulator enables analyses and simulations of the receiver critical algorithms and architecture design, such as acquisition and tracking, AltBOC performance, multipath and interference analysis, etc. Figure 1 and Figure 2 show the simulator user interface and the Simulink upper-level model, respectively. Auto-coding techniques are used to produce a C code version of the Bit-True GNSS SW Receiver. Once the core technologies design and implementation in Matlab/Simulink is complete, a C-code version of the selected SW receiver configuration is obtained, thus enabling extensive simulations of the chosen receiver architecture.

2. GNSS Environment and Navigation Simulator

A lightened version of the SW receiver, implemented in C-code, is oriented to application developers who only need external access to raw data (i.e. pseudorange and carrier phase). It includes realistic characterisation of the effect of the different error components depending on the type of terminal and GNSS receiver configuration. It is possible to configure the GNSS constellation (both Galileo and GPS, allowing the derivation of the optimal algorithms for a combined PVT solution.), the environmental conditions, satellites and receiver characteristics, and the navigation algorithms.

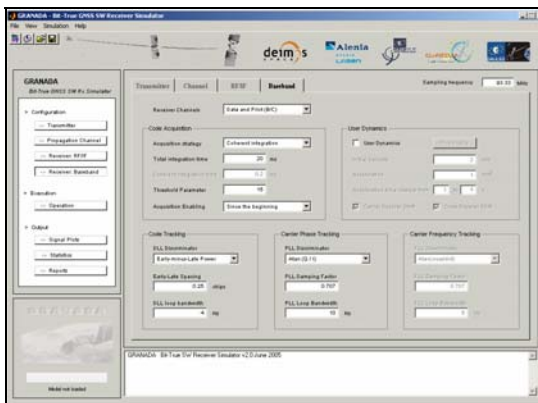


Figure 1. GRANADA Bit-True simulator user interface

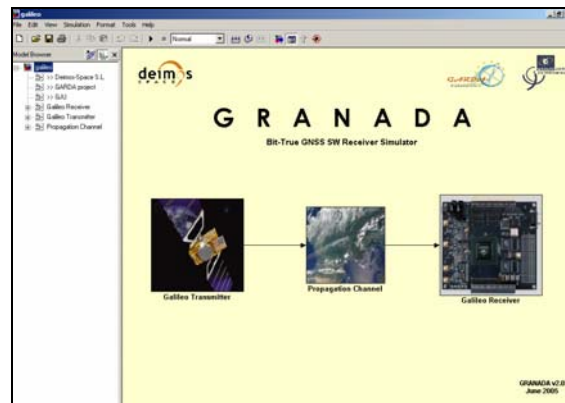


Figure 2. GRANADA Bit-True simulator Simulink Model

GRANADA BIT-TRUE SIMULATOR ARCHITECTURE

The GRANADA Bit-True SW Receiver Simulator recreates in detail the signal processing stage of Galileo receivers using Simulink modules, allowing to test several acquisition and tracking strategies. The Simulink based design of the tool is characterised by its modularity, which allows to replace the implemented system by the user own architecture. Only one carrier is simulated, in a bi-channel receiver (single frequency, data and pilot); although all the Galileo carriers and channels can be selected. The different modules of this simulator include signal generation, noise insertion, multipath model, interference addition, RF Front-end modelling, analog-to-digital conversion, IF down-conversion, carrier-to-noise density ratio estimation, code acquisition, code and carrier tracking, and data detection. For all these modules, assumptions and algorithms have been adopted and implemented as baseline in the GRANADA SW Receiver Simulator. Thanks to the flexibility and modularity of the tool, the user can modify these baselines.

Signal Generation

On the fly baseband signal generation and IF up-conversion is performed in the transmitter module of the simulator. For each Galileo carrier (E5, E6, and L1) [6], it includes code generation, data and BOC modulation, channel multiplexing, and IF filtering. As an example, Fig. 3 shows the AltBOC modulator for E5 AltBOC and L1/E6. Signal generation has been implemented following Galileo SIS-ICD. The code phase insertion block has been highlighted.

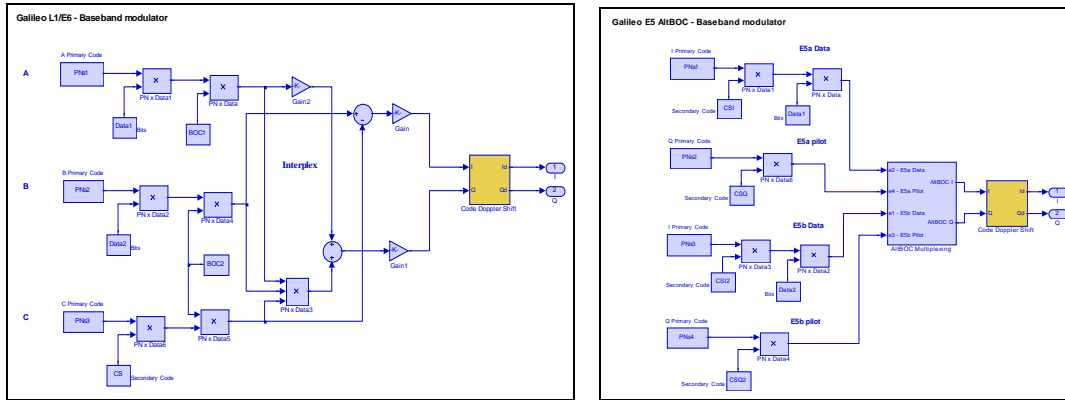


Figure 3. Simulink model for L1E6 and E5 AltBOC baseband modulators

Code Doppler shift insertion

Due to both satellite and user dynamics, the incoming Galileo signal is distorted by a Doppler shift that produces an additional error in the pseudorange and carrier phase measurements. Since in any conventional receiver carrier Doppler shift is estimated by the FLL/PLL loops or using additional carrier aided techniques, code frequency offset can be the main error source due to system dynamics. This problem is expected to be more critical for Galileo than for current GPS L1 C/A receivers [4], since the integration for GPS is significantly longer than what is expected for Galileo, while the chip-rate is much higher for Galileo (particularly in E5, with a chip-rate of 10.23 Mcps).

In the simulator, code Doppler shift is introduced in the transmitter after baseband multiplexing. Knowing the user velocity and acceleration, the simulator model computes the accumulated delay due to Doppler shift in order to apply it to the I- and Q- components of the generated baseband signal. Since the sampling rate of this signal (about 90 MHz) is not enough to include directly a variation of the ranging code chip rate due to the code phase error, a new technique has been developed to simulate this effect.

The Code Doppler block of Figure 3 is expanded in Figure 4. Both the I- and Q- components of the generated baseband signal are delayed a number of samples that are calculated from the user defined initial velocity and acceleration. This insertion of code Doppler shift is independent from carrier frequency offsets.

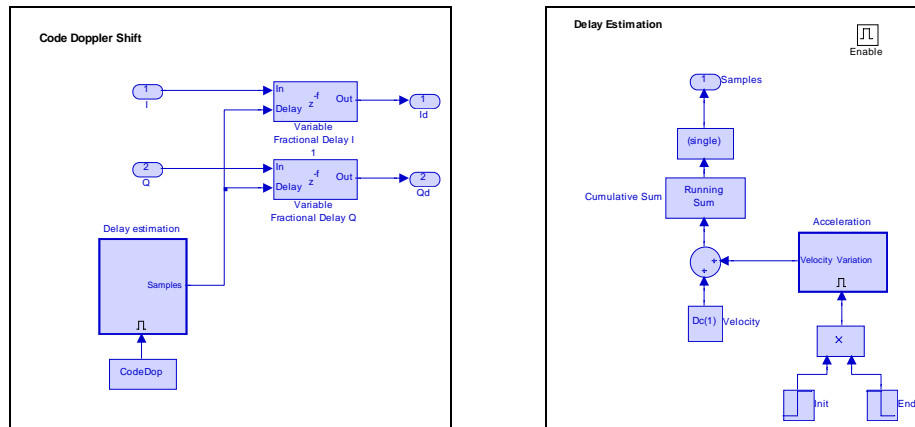


Figure 4. Insertion of the code Doppler shift in the GRANADA bit-true simulator

Receiver Architecture

A simplified block diagram of GRANADA receiver architecture is shown in Fig. 4. The three functions of BOC demodulation and chip-pulse matched filtering are integrated into a three-stage processing architecture. The I/Q baseband signal is converted to a complex-valued signal before the accumulation over a half-slot period (the slot time is half a period of the BOC subcarrier). The lengths of the first accumulators are integer values regulated by the DLL to achieve code tracking. These values are not constant in time, but in average they are equal to the true samples/slot that is determined by the frequency plan. The processing then continues with BOC demodulation followed by chip-time accumulation, despreading, and bit-time accumulation. The carrier phase and frequency recovery block works in a short-loop mode, removing carrier

phase error and Doppler shift just before the code correlator. Although not shown in Figure 4, code acquisition is also implemented in the simulator. This architecture is common to all Galileo carriers (avoiding the BOC demodulation stage in BPSK channels).

GRANADA is a bi-channel simulator that is able to process simultaneously two branches (the data and pilot channels) of this receiver architecture. In this paper, simulations comparing the receiver performance using only the open service data channel or combining the data and pilot are presented. To implement it, the DLL code phase outputs of both channels are combined to provide a less noisy input to the half-slot accumulator.

AltBOC demodulation

For E5 AltBOC modulation, two solutions are implemented to allow core technologies developers the higher flexibility in the optimisation of this new multiplexing scheme: single-side-band (SSB) processing, and direct IF sampling. In the first case, the demodulation of the receiver input signal is performed in the respective side-band centre of E5a or E5b. One of the two main lobes of the spectrum is placed at IF, so that the IF filter cancels the other (SSB detection). The digital section (acquisition and tracking) after the IF stage is the conventional non-return to zero (NRZ) Galileo demodulator. In Direct IF sampling, the demodulation of the receiver signal is performed centre in the E5 band, allowing dual-sideband coherent demodulation of E5a+E5b. Acquisition and tracking can be obtained by using an AltBOC(15,10) as reference signal.

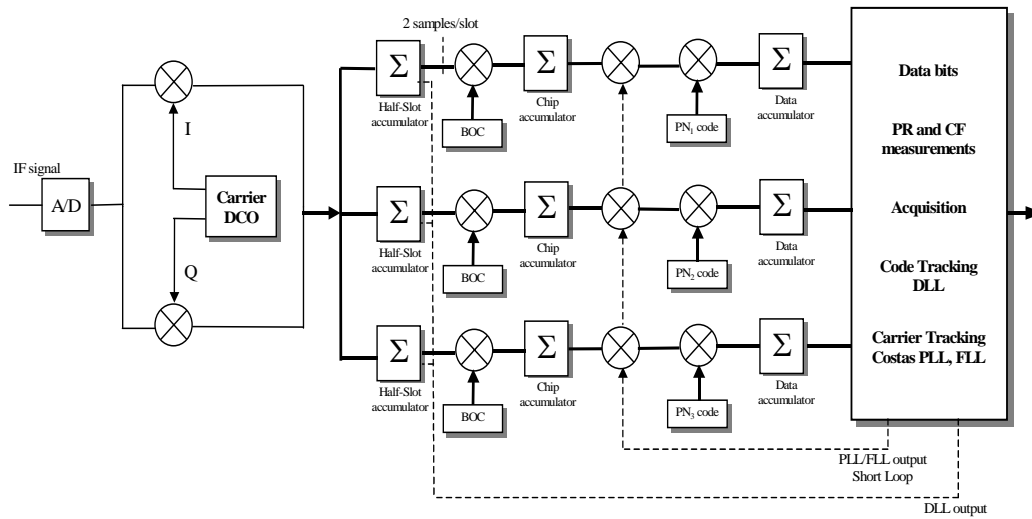


Figure 5. Simplified block diagram of GRANADA receiver architecture

Code Tracking

The code tracking loop has to locate the optimum chip rate signal sampling instant to provide optimum data detection and increase the accuracy of positioning in the navigation process. The Delay Lock Loop (DLL), which uses the early, late and prompt outputs of the half-slot accumulator, and a first order loop filter performs this code tracking. GRANADA implements three types of DLL discriminators: Early-minus-Late (EmL) Power, dot product, and EmL coherent. The EmL power, which has been used to obtain the simulations results provided in this paper, has an output totally independent on data modulation and of carrier phase estimation. The error function is given by:

$$e(k) = [I_E^2(k) + Q_E^2(k)] - [I_L^2(k) + Q_L^2(k)],$$

where I_E and Q_E are the quadrature components of the early chip correlator output, and I_L and Q_L are the components of the late chip correlator output. The loop filter is based on the following recursive equation:

$$\varepsilon_{k+1} = \varepsilon_k - \gamma e(k)$$

where $e(k)$ is the error signal generated by the DLL discriminator, ε_k is the normalised k-th estimation of the signal delay, and the step-size γ is obtained by

$$\gamma = \frac{4B_L T_L}{A(1+2B_L T_L)}$$

where B_L is the loop bandwidth, and T_L is the integration time. The slope of the loop error characteristics for the EmL power discriminator is given by

$$A = -(4X + 2X^2 \cdot \Delta)$$

where Δ is the early-late spacing in chips, and $X=1-2L_{BOC}$ (being L_{BOC} the number of slots per chip for the corresponding type of BOC modulation).

Carrier Tracking

A short-loop Costas Phase Lock Loop (PLL) and a Frequency Lock Loop (FLL) perform carrier phase and frequency tracking respectively in the receiver architecture implemented in GRANADA. Different discriminators can be selected, as well as the parameters of the second-order loop filter (loop bandwidth and loop damping factor). The resulting carrier phase error, obtained as the sum of the PLL and FLL outputs, rotates the incoming complex-signal phase before the chip accumulator subsystem (see Figure 5).

The PLL discriminator takes the output of the bit-time accumulator and generates a carrier phase error signal $e(n)$, which is the input of the second-order loop. The simulations have been performed using a atan(Q/I) discriminator. The output of the loop filter is the carrier phase error $\hat{\theta}(n)$, obtained as

$$\begin{aligned}\mu(n) &= \mu(n-1) + \gamma(1+\rho)e(n) - \gamma e(n-1), \\ \hat{\theta}(n) &= \hat{\theta}(n-1) + \mu(n),\end{aligned}$$

where the loop parameters γ and ρ can be related to the loop noise bandwidth B_L and to the loop damping factor ζ as follows

$$\zeta = \frac{(1+\rho)\sqrt{\gamma A}}{2\sqrt{\rho}} \quad B_L T_L = \frac{2\rho + \gamma A(2+\rho)}{2[4 - \gamma A(2+\rho)]},$$

where A is the slope of the loop error characteristic, and T_L is the integration time or the PLL updating rate.

SIMULATIONS AND ANALYSES

Taken benefit of GRANADA capabilities, a simulation campaign has been executed to characterise the effect of the code Doppler shift in the L1 and E5 open service channels. L1 will be probably the main frequency to be used in mass-market receivers, while the study of E5 signals is interesting because of the new AltBOC modulation and their highest chip rate. An early-minus-late power DLL discriminator and a first order loop filter are used in the code tracking stage, considering an early-late spacing of 0.1 chips. For simulation purposes, carrier Doppler shift has been disabled.

Figure 6 shows the pseudorange error as a function of the relative velocity for the Galileo L1 BOC(1,1) channel for different carrier-to-noise density ration and for DLL loop bandwidth of 5 Hz and 15 Hz. It can be observed the degradation of the system as a function of the relative velocity of the receiver with respect the transmitter satellite. Figure 7 shows results considering a noiseless channel for both E5 and L1 signals and different loop bandwidths. It can be observed that E5 is more sensitive to code Doppler shift due to the higher chip rate of this signal.

From these results, it can be observed that there is a trade-off between the tracking errors due to thermal noise and the errors due to code Doppler shifts. The close-loop noise variance due to thermal noise is given by [5]

$$\sigma_r^2 = \frac{c^2 \cdot B_L d}{2S/N_0 R_c^2 K_{BOC}} \left(1 + \frac{2}{(2-d \cdot K_{BOC})C/N_0 T_i} \right) \quad [\text{m}^2]$$

where c is the speed of light, B_L is the loop noise bandwidth, d is the early-late spacing in chips, R_c is the chip rate (1.023 Mchips/s for L1 and 10.23 Mchips/s for E5), T_i is the predetection integration time (4 ms for L1

and 1 ms for E5; these values are chosen to match the corresponding code lengths), C/N_0 is the carrier-to-noise density in Hz, and K_{BOC} is a parameter that depends on the signal modulation of the selected Galileo channel ($K_{BOC}=4m/n$ for BOC(m,n), and $K_{BOC}=1$ for BPSK). Hence, the error is proportional to the loop bandwidth. On the other side, as it is demonstrated in Figure 7, a large B_L allows the receiver to track higher dynamics, being more robust against code Doppler shift. In addition, a small loop bandwidth may increase the probability of lock lost when the DLL is not able to follow the system dynamics.

In this way, a degradation of the receiver performance is expected under high dynamics conditions due to Doppler shift because of the necessary increasing of the DLL loop bandwidth. However, different strategies must be further investigated in order to reduce this degradation:

- Increase the DLL loop filter: a second-order filter could reduce the pseudorange error due to code Doppler shift.
- Code aided loops: using the Doppler information provided by the tracking loops, the DLL generates codes with a corrected chip rate. This technique increases the receiver complexity, but allows a considerable reduction of the DLL loop bandwidth.

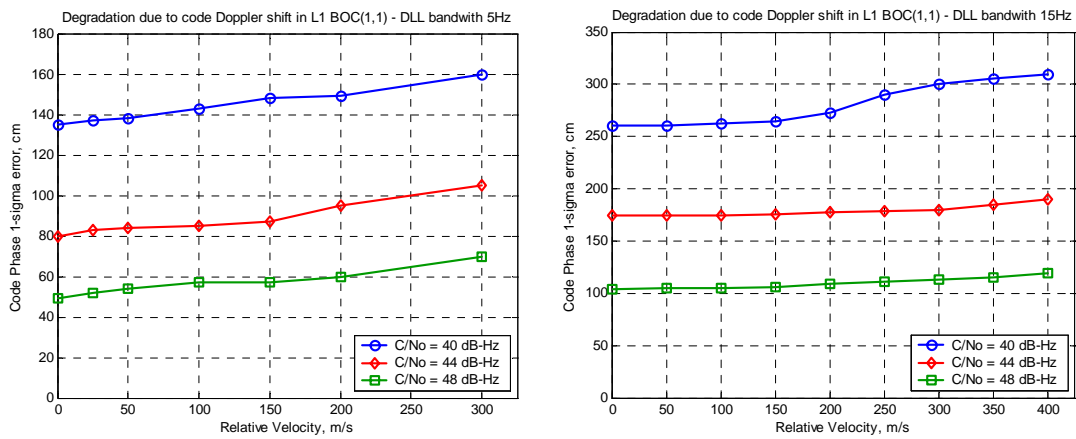


Figure 6. Degradation of the code phase measurements due to code Doppler shift

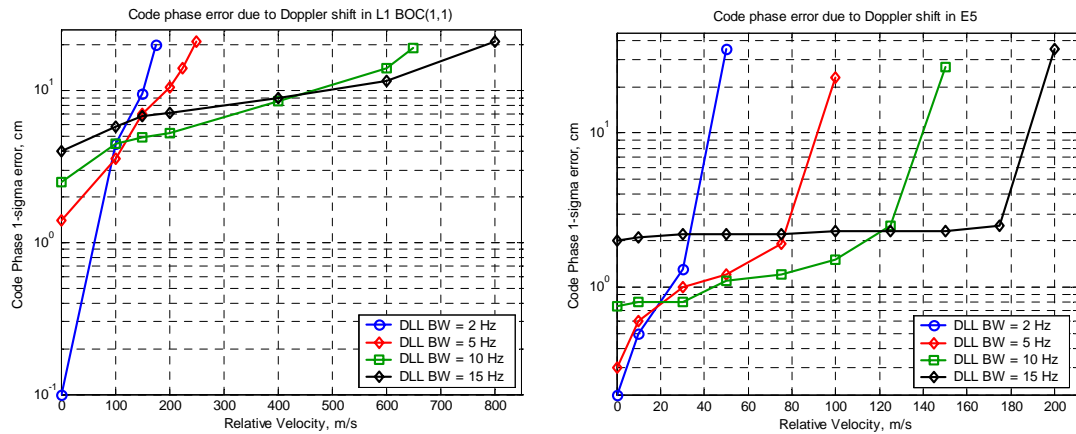


Figure 7. Code phase error due to Doppler shift in a noiseless channel.

CONCLUSION

GRANADA is the first open tool, running on a commercial PC under Windows, to precisely (bit-true) replicate a GNSS receiver HW and algorithms, integrating both GPS and the new Galileo signals. The Galileo Joint Undertaking is in position to grant licenses to the user community and application developers, proposing GRANADA as a reference SW suite for GNSS receivers. GRANADA also constitutes a first step towards an integrated SW radio receiver.

After a general introduction on the suite, the GRANADA receiver architecture has been presented. The simulator has been used for analyse the effect of code Doppler shift in the Galileo L1 and E5 signals. The results show an appreciable degradation of the system in high dynamics conditions, which suggests further investigation on this problem in order to minimise the error in the pseudorange measurements.

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