Simulation of GPS and Galileo Architectures for Anti-jamming and Multipath Analysis

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Abstract

The launch of the new European satellite-positioning system named Galileo gives much potential for innovative developments such as hybrid architectures (e.g., combined GPS/Galileo receivers, new concepts like Software Defined Navigator). In this context, the use of a generic simulator proves to be essentially useful for signal-processing analysis and for the design of new architectures of future multi-standard navigation receivers. The simulator proposed in this paper is developed on the basis of Matlab/Simulink® software and makes possible the simulation of a completely digital architecture for GPS and Galileo receivers including the simulation of all sources of satellite signals and a generic channel of disturbances (e.g., multipath, Doppler, jammer, atmospheric delay, etc.) Moreover, the simulator is completely hierarchical allowing the user to handle all the sections in an interactive mode during the simulations. It should be mentioned that the simulator is very useful and effective for the analysis of multipath and jammer effects on the behavior of the Phase-Locked Loop (PLL) and Delay-Locked Loop (DLL) and for the evaluation of the performances of various pre-correlation filters for the new generation of GPS/Galileo receivers. Particularly, the simulator considered in this paper allows for the analysis of Amplitude Domain Processing (ADP) and FADP (ADP in the frequency domain) filters to clarify their performances and complexity of implementations. This paper will briefly present the simulator and a generic demonstration concerning the use of the simulator.

continued on page 14

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1. Introduction

At the origin of the Matlab/Simulink® simulator is a generic architecture of a GPS receiver largely approached in the literature (Kaplan, 1996; Parkinson et al., 1996) with all the possibilities offered by the powerful tools of Matlab and Simulink®. Since the European Galileo system is under development, most recent publications on Galileo (European Space Agency reports, conferences, papers, magazines) represent an invaluable source of information for the design of new hybrid architectures. Also, while the Galileo signal definitions are still not completely approved, the definition of a software-defined navigator is the ideal way for receiver design.

In the second section of this paper, the design of a generic satellite navigation simulator is briefly presented. A hybrid GPS/Galileo architecture is proposed and simulated including a C/A (Course/Acquisition) code for GPS and a BOC(1,1) (Binary Offset Carrier) code for Galileo. The description of the model considered and its general functionalities are given, as well as a description of the signal sources. In the same section, the digital receiver is described from the structural and functional point of view.

The third section is dedicated to anti-jamming and multipath analysis, some examples of robustness scenarios are also presented. The analysis is done in the presence of a channel of disturbances including CWI (Continuous Wave Interference) jammers, and multipath signals. Finally, the paper will present the gain achieved using a pre-correlation filter such as the FADP (Amplitude Domain Processing in the frequency domain) digital filter (Landry, 2001).

The last section of the paper is devoted to some conclusions.

2. GPS and Galileo Receiver in Simulink®

The simulation of a GPS/Galileo communication channel in Simulink® is based on the following principles:

(a) Generation of the GPS and Galileo baseband signals made in accordance with known or possible modulation schemes (Hein et al., 2002; Kaplan, 1996).

(b) Transposition of the signal spectrum from baseband to Intermediate Frequency (IF) allowing real digital signal processing.

suite de la page 13

Résumé

L'apparition du nouveau système européen de navigation par satellites Galiléo offre beaucoup de potentiel à des développements innovateurs tels que les récepteurs hybrides (par ex. récepteurs combinés GPS/Galiléo, nouveaux concepts comme Software Defined Navigator). Dans ce contexte, l'utilisation d'un simulateur générique s'avère indispensable pour l'analyse de traitement du signal et pour la conception de nouvelles architectures pour des récepteurs futurs de navigation multi-standard. Le simulateur proposé dans cet article est développé en Matlab/Simulink^MD et permet la simulation d'une architecture entièrement numérique de récepteurs GPS et Galiléo. Cette architecture inclut la simulation de toutes les sources de signaux satellitaires et un canal générique de perturbations (par ex. multi trajets, Doppler, brouilleurs, délai atmosphérique, etc.). En plus, le simulateur est complètement hiérarchique et permet à l'utilisateur de gérer toutes les sections dans un mode interactif pendant les simulations. Le simulateur est très utile pour l'analyse des effets des multi trajets et des brouilleurs sur le comportement des boucles de phase (PLL, Phase-Locked Loop) et de code (DLL, Delay-Locked Loop) et pour l'évaluation des performances de différents filtres de pré-corrélation pour la nouvelle génération de récepteurs GPS/Galiléo. Le simulateur utilisé permet en particulier d'effectuer l'analyse de filtres ADP (Amplitude Domain Processing) et FADP (ADP dans le domaine des fréquences) afin de déterminer leurs performances et complexités de mise en œuvre. Cet article présente brièvement le simulateur et une démonstration générique concernant son utilisation.

(c) Introduction of dynamic disturbances (Doppler effect) separately on the carrier and on the code directly at the source module.

(d) Simulation of a channel of disturbances including thermal noise, jammers, attenuation of the signal, and multipath.

(e) Modeling the Phase-Locked Loop (PLL) and the Delay-Locked Loop (DLL) and all other receiver modules of a generic GPS receiver.

(f) Design of an analysis block by using the possibilities offered by Simulink® (spectrum analyzer, digital scope, correlation, display, etc.).

These principles are discussed and generalized in the following sub-sections.

2.1. Description of the Model and General Functionalities

While being based on the principles mentioned, the simulator is composed of the following four distinct parts:

(a) Source of the GPS and (or) Galileo signals (according to a specific number of available satellites).

(b) Channel of disturbances.

(c) Receiver module including GPS and Galileo channels (AGC = Automatic Gain Control).

(d) Analysis module.

The interaction between these blocks is represented in **Figure 1**.

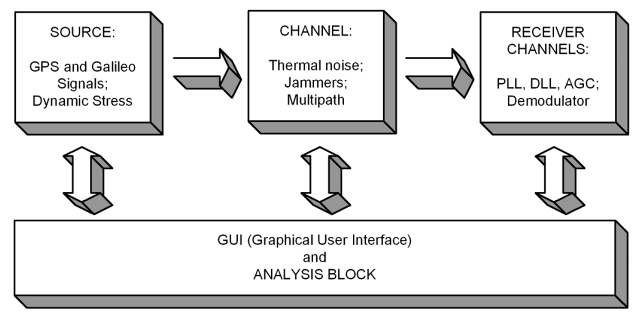

Figure 1. Principle of simulation and interaction.

The source module generates a pseudo-random-noise (PRN) sequence modulated with the data and transposed on an intermediate frequency (for each satellite signal). The frequency and the phase of the transmitted signal vary according to the selected disturbances (Doppler dynamics). The source module can generate multiple signals according to the number of desired satellites or according to the desired system to be analyzed (GPS and (or) Galileo).

The main role of the channel of disturbances is to attenuate the signal, to add the thermal noise, the jammers, and the multipath to degrade the signal and to make the model as realistic as possible. The jammers and the multipath parameters are controlled in an interactive mode during the simulation process.

Within the framework of the presented paper, the receiver is composed of one C/A channel (GPS) and two E2-L1-E1 channels (Galileo). These two Galileo channels represent two different architectural approaches in the design of the receiver, which will be described below. The main elements in the receiver channel are the PLL and the DLL. In general, the behavior of these loops determines the performances of the receiver and the robustness of the system. It should be mentioned that these digital loops are our main concern during the analysis of robustness, dynamics, and performance against interference, jammers, and multipath. In fact, without strong and precise carrier and code phase measurements, the navigation algorithm will introduce positioning errors.

To make a robustness study with respect to the various jammers, the model presented also contains an ADP filter in the frequency domain, named FADP. The mode of interaction with the simulator is carried out using the analysis block that enables to change the parameters of the simulator and to collect the results. The first three parts of the simulator (except the analysis block) constitute the main elements of the GPS/Galileo communication system. **Figure 2** represents a simplified view of this generic architecture. The simulated architecture considered in this paper for the analysis of robust scenarios is presented in **Figure 3**.

Introducing dynamic stresses on the code and on the carrier separately facilitates the analysis of the reaction of the loops to these disturbances. In this case, we can study the behavior of only one loop (PLL or DLL) without taking into account the existing interaction between the loops. To ensure constant amplitude of the signal at the input of the receiver, we use an AGC block.

The simulated architecture is completely digital, using the natural sampling process of the Simulink® tool. The sample time is chosen according to the highest frequency of the simulated signal and with respect to the simulated source of signals (GPS or Galileo).

To avoid a double frequency conversion (up-conversion at the transmitter and down-conversion at the receiver), which can be done digitally nowadays, we use the Binary Phase Shift Keying (BPSK) modulation directly on the IF. The value of this frequency is chosen to respect the symmetry of the signal spectrum (see **Figure 4**).

Functional Description of the Source of Signals

The source of the signals generates data-modulated code that is transposed on the intermediate frequency (**Figure 4**). To simplify the analysis in this paper, the simulation was reduced to the C/A signal for the GPS system and the E2-L1-E1 signals for the Galileo system. The M code and P code in the GPS system are not taken into account but their implementation is always possible. **Figure 5** represents the spectrum of the generated GPS and Galileo signals.

Modulation schemes of the E2-L1-E1-generated signal are described in Hein et al. (2002). For practical use and to accelerate the simulation, the flexible BOC(*n*,*m*) (Binary Offset Carrier) signal is replaced by BOC(1,1). In this way, it is obvious that the smallest sample frequency, F_s, that is double the signal bandwidth, should be greater than 8.184 MHz (see **Figure 5**). For simulations presented in this paper, the value of the sample frequency was about 12.93 MHz. The Simulink® implementation of the E2-L1-E1 signal generation is presented in **Figure 6**. The BOC(*n*,*m*) signal generation is widely

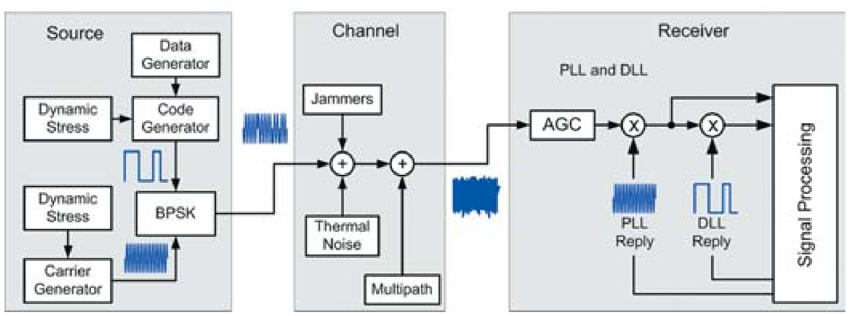

Figure 2. Simplified architecture of the GPS/Galileo communication system.

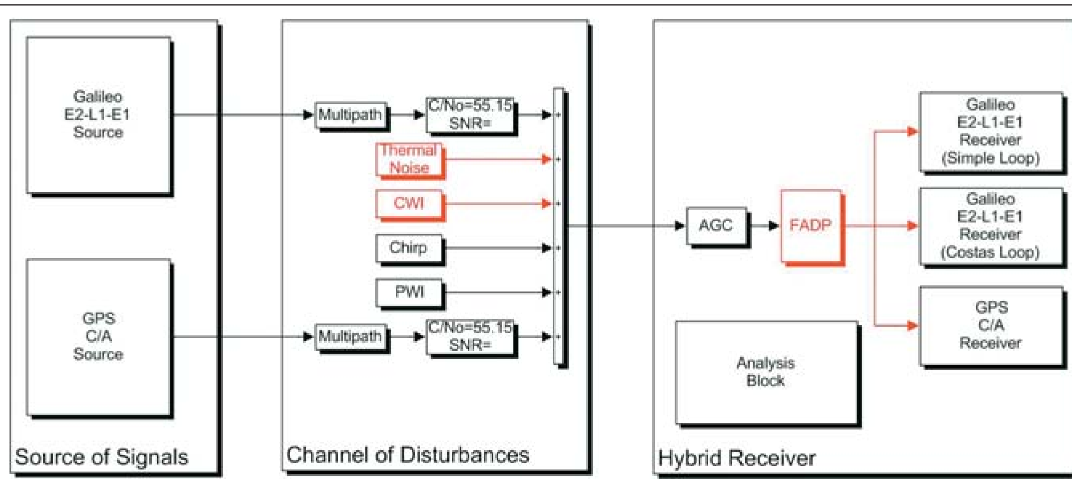

Figure 3. Simulated architecture for robustness scenarios analysis (highest level).

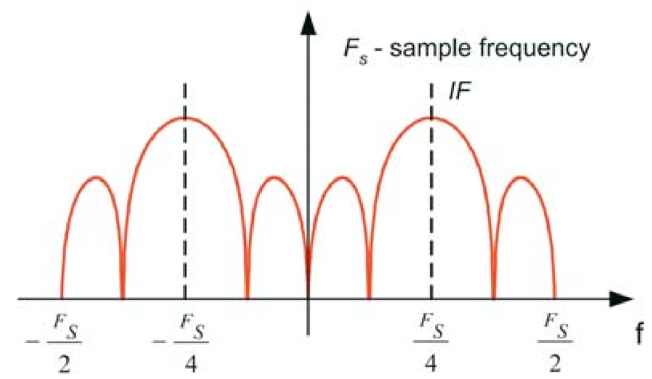

Figure 4. IF baseband simulation principle.

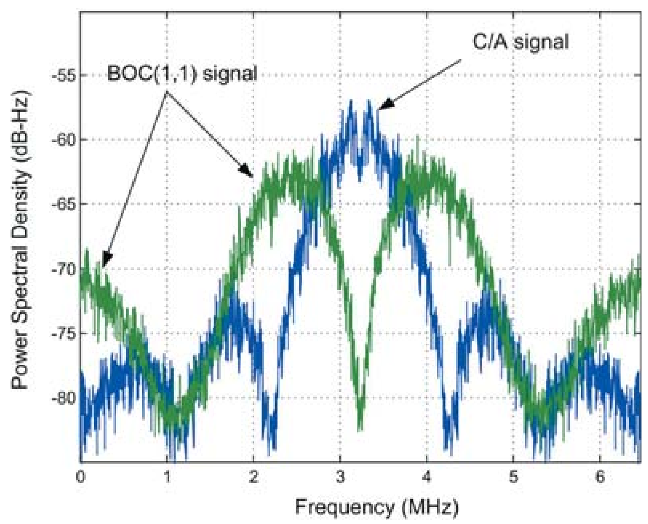

Figure 5. Spectrum of the generated signals.

described in the literature (Betz, 1999; Ries et al., 2002) and will not be mentioned in this work.

It is interesting to note that the Doppler-frequency simulation on the carrier and on the code is based on the following expression:

$$S_{\mathrm{IF}} = \cos\left(2\,\pi\, f_{\mathrm{IF}}\, t + \frac{2\pi}{\lambda} D_{ir}\, t + \theta_{\mathrm{in}}\right) \tag{1}$$

where S_{IF} is the IF signal, f_{IF} is the intermediate frequency (Hz), D_{ir} is the radial instant distance between receiver and satellite (m), λ is the carrier (code) wavelength (m), and θ_{in} is the initial phase value (rad).

2.2. Structure and Functional Description of the Digital Receiver

The architecture of the GPS receiver is widely reflected in the literature and will not be described here (see, for example, Kaplan (1996)). Further, the simulated architecture of the Galileo channels will be discussed. The chosen approach has the advantage that one of the three transmitted codes in the E2-L1-E1 band is data free. So, without data transition in the signal, it is possible to use a simple phase loop (one arm) instead of the Costas loop or the atan2 discriminators in a quadratic loop improving the tracking threshold of the PLL. The two diagrams of the simulated Galileo architecture are presented in **Figure 7** and **Figure 8**. The comparative study of these two architectures is under consideration and will be presented in future works.

In this paper, the antijamming and multipath analyses are done in a Costas loop configuration of the receiver. As shown in **Figure 6**, the pilot BOC(1,1) signal and the BOC(15,2.5) data-modulated signal are transmitted in phase, while the BOC(1,1)

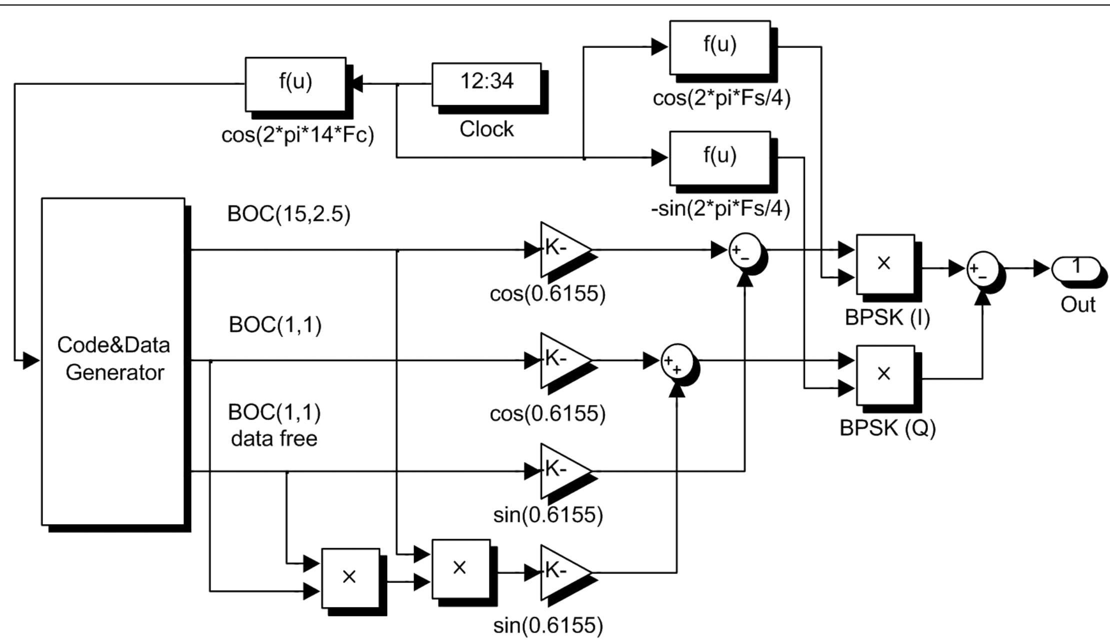

Figure 6. Modified hexaphase modulation.

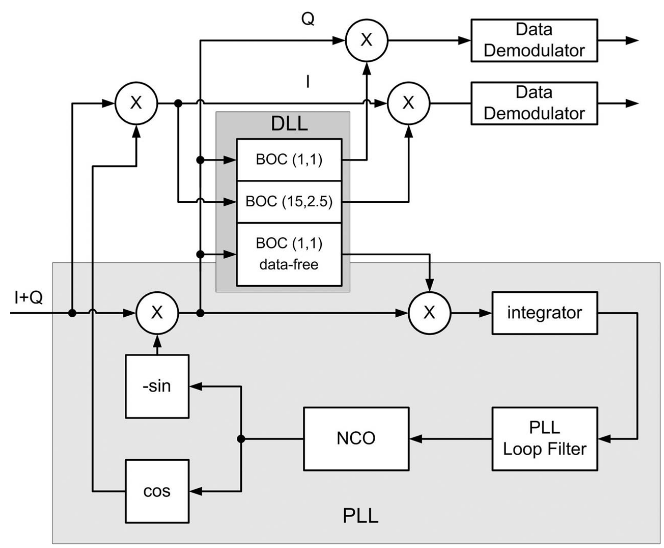

Figure 7. Galileo receiver (simple PLL).

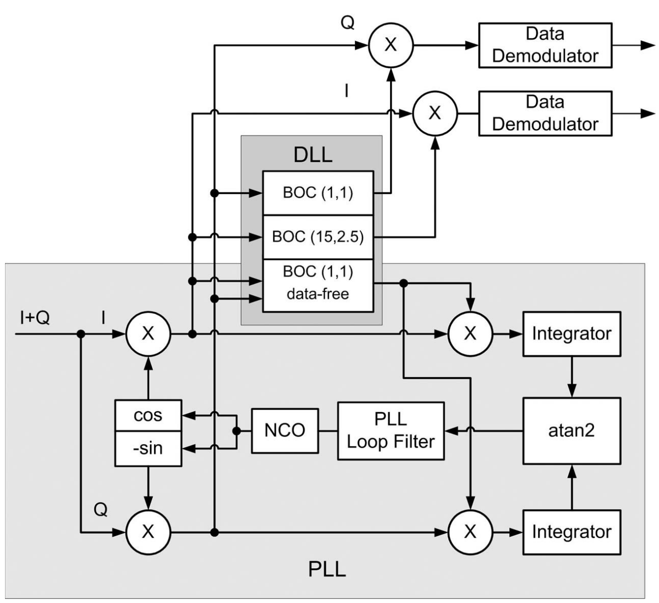

Figure 8. Galileo receiver (Costas PLL).

data-modulated signal is transmitted in quadrature. To synchronize the loops and extract the transmitted data, the DLL generates the exact replicas of the transmitted codes using BOC(n,m) modulation. The implemented diagram of the simulated receiver architecture in Simulink® is presented in **Figure 9**. The generic architecture of the DLL is the same as in the case of the GPS system but adapted for the correlation function of the BOC(15,2.5) and BOC(1,1) signals.

3. Anti-jamming and Multipath Analysis

This section presents a generic example showing how the simulator can be used for robustness analysis in the presence of interferences and multipath. Also, this example shows the effectiveness of the simulator for anti-jamming filter evaluation. For this purpose, an adaptive FADP (Frequency Amplitude Domain Processing) anti-jamming filter is inserted in the receiver channel.

3.1. Anti-jamming Analysis

It is known that functional disturbances in the receiver, in the presence of interferences, are mainly due to the degradation of the signal-to-noise ratio (C/N_0). But the jammers can also offset the signal detected in the digital receiver. This effect is difficult to estimate by means of theoretical analysis only. The use of the simulator instead allows measuring of the C/N_0 ratio in conjunction with an estimate of the degradation of the detected signal. Without special techniques, the offset caused by the jammers changes the discriminator output and leads to lose of tracking. An example of this particular situation is presented in **Figure 10**. As can be seen in **Figure 10b**, the asymmetry of the detected signal, especially in the imbedded loops, increases the level of the noise at the discriminator output. This effect can be noted even in the case when the jammers are not in the main lobe of the received signal.

Further, the C/N_0 ratio degradation will be estimated in the presence of CWI jammers at the input of the hybrid receiver. **Figure 11** represents the C/N_0 ratio as a function of the JNR (jammer-to-noise ratio) for three types of signal: BOC(1,1) pilot, BOC(1,1) data-modulated, and C/A. In this example, CWI jammers are used and the JNR for each of them is varied from –24 to 21 dB. We should remember that the JNR is defined as the ratio between the power of the jammer and that of the thermal noise at the input of the receiver. For simplicity, this ratio is expressed in decibels. **Figure 11a** represents the case when one CWI jammer is placed in the main lobe of the C/A code. It should be noted that, in this case, the BOC(1,1) signal is less sensitive to this interference. It should be expected that the impact of jammers on the BOC(1,1) signal will be increased if the jammers are placed in the main lobes. **Figure 11b** and **Figure 11c** reflect this case. One and two CWI jammers are placed on the main lobes of the BOC(1,1) data-modulated signal, the corresponding results being presented in **Figure 11b** and **Figure 11c**, respectively. While the BOC(1,1) signal is more robust than the C/A signal, its C/N_0 degrades quickly with the JNR and without an adaptive filtering the signal-to-noise ratio can reach the tracking threshold.

The following example demonstrates the use of the simulator for anti-jamming filter analysis. For the purpose of this paper, the FADP adaptive filter is used. A thorough description of the filter can be found in Landry (2001), the

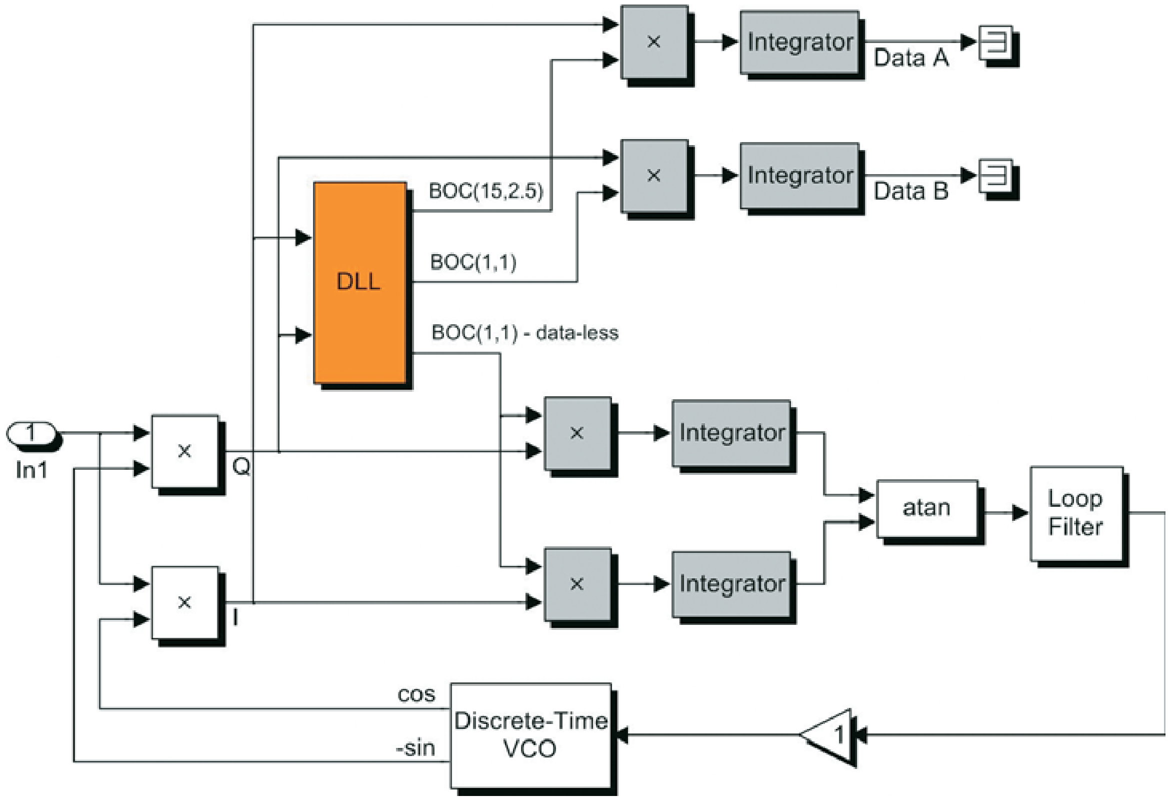

Figure 9. Receiver in Costas PLL implementation.

generic block diagram of this filter is presented in **Figure 12**. The main part of this filter is the ADP block where the statistical processing of the amplitudes is done to mitigate signals with a non-Gaussian probability distribution function. As the processing is done in the amplitude domain, the gain of the filter is not sensitive to the frequency of the jammers and in these terms the FADP can be considered as an adaptive filter.

If the frequency of the jammer does not affect the functionality of the filter, the position of the jammer frequency in the signal spectrum determines its rate of degradation. **Figure 13** represents the C/N_0 ratio as a function of the jammer frequency at the filter output. In this test, the frequency of a CWI jammer with the JNR = 20 dB was varied along the receiver frequency band. It should be noted that the degradation of the C/A signal is higher than that of the BOC(1,1) signal. It should be remembered that the density of the BOC(1,1) spectral lines is twice the density of the C/A spectral lines (due to the BOC signal sub-carrier), resulting in a power density of the BOC(1,1) smaller than the one of the C/A code. The C/A code has a few strong lines that render it more vulnerable to CWI interferences.

The use of the FADP filter drastically improves the signal-to-noise ratio in the receiver. **Figure 14** shows the C/N_0 ratio as a function of the JNR with and without the FADP filter. For this test, 10 CWI jammers were added to the incoming signal. From **Figure 14**, it can be seen that the degradation of the C/N_0 ratio for a JNR = 20 dB is less than 3 dB. The FADP filter has a threshold of about –14 dB of the JNR.

Figure 15 shows the JNR at the output of the filter as a function of the JNR at the input. In other words, this relation represents the gain of the filter. For example, for a JNR at the input of 20 dB, the JNR measured at the output is about –28 dB. This gives a gain of the FADP filter about 48 dB.

Figure 16 shows the spectrum of the mixed signal composed from GPS and Galileo signals, thermal noise, and CWI jammers at the input of the FADP filter. The CWI jammers are completely mitigated after the FADP filter, as can be seen in **Figure 17**. This example can be extended to the analysis of other types of jammers and (or) to different anti-jamming filters.

3.2. Multipath Analysis

The following example shows the use of the simulator for the code multipath error analysis. For this purpose, a multipath wave was simulated with different signal strengths and with different phase shifts. To obtain the multipath error envelope, this wave was delayed in the range 0–450 m that corresponds to a maximum delay of 1.5 chips. The tests were done using the dot-product code discriminator.

Figure 18 shows the multipath error envelope for the C/A signal. For this example, the ratio of signal power P_S to multipath power P_M (expressed in decibels) is chosen in the range 3–10 dB. The common correlation spacing d = 0.1 chip has been considered. The correlation spacing d is defined as the delay between the early and the late replicas of the incoming

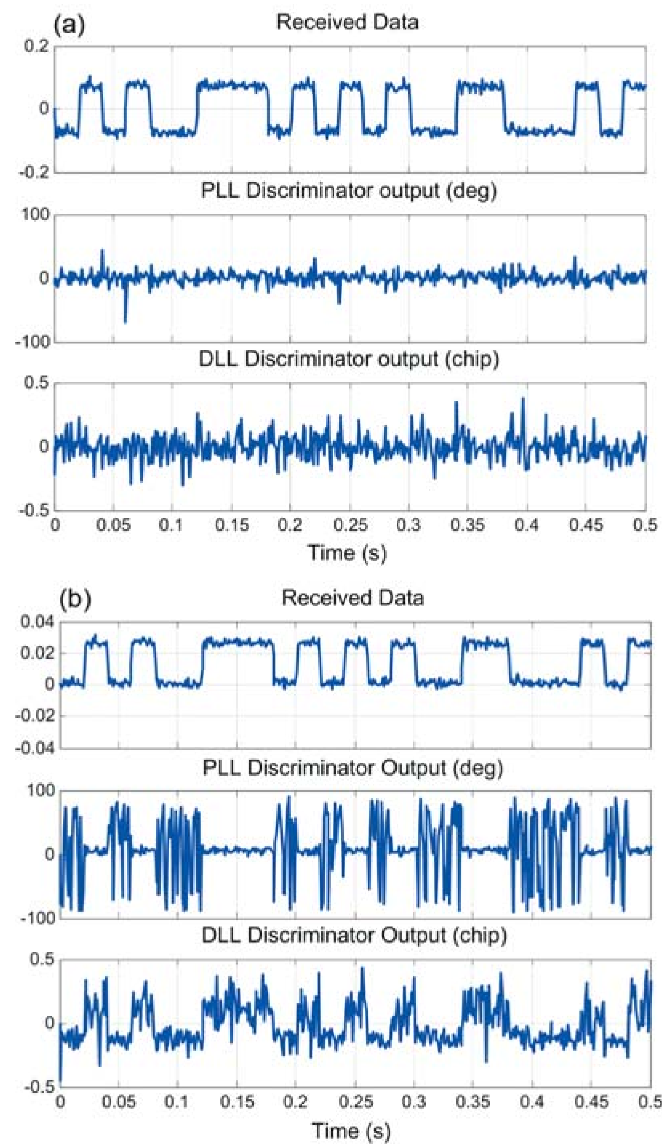

Figure 10. Signal offset without (a) and with (b) CWI jammers.

code. To avoid the correlation peak deformation, the receiver bandwidth for this test was chosen to be about 40 MHz.

Figure 19 represents the multipath error envelope for the BOC(1,1) signal. As can be expected, the BOC(1,1) signal is less sensitive to multipath effects compared with the C/A signal. For example, for a signal strength difference of 10 dB between the signal and the multipath powers, the multipath error can be less than 6 m (for 150–300 m of multipath delay).

Figure 20 and **Figure 21** represent the multipath error envelope for a signal strength difference of 10 dB and for different correlation spacing *d*. As we remark, the multipath error increases with the value of the correlation spacing and for $d = 0.2$ it can reach about 9.4 m for the C/A as well as for the BOC(1,1) signals.

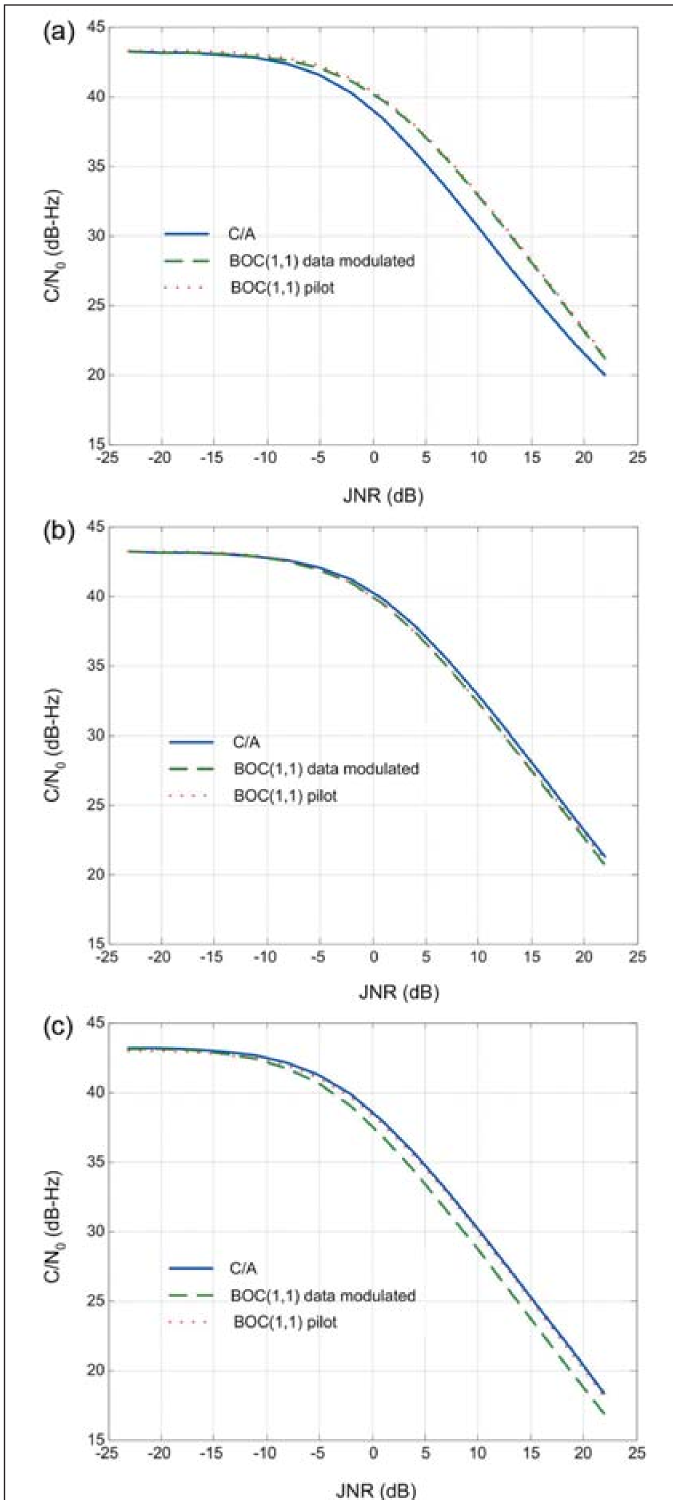

Figure 11. C/N_0 as a function of JNR. (a) One CWI in the main lobe of C/A; (b) One CWI in the main lobe of BOC(1,1); (c) Two CWI in the main lobe of BOC(1,1).

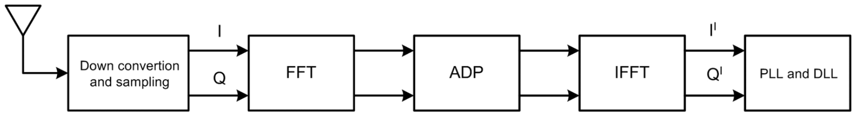

Figure 12. Generic block-diagram of the FADP filter.

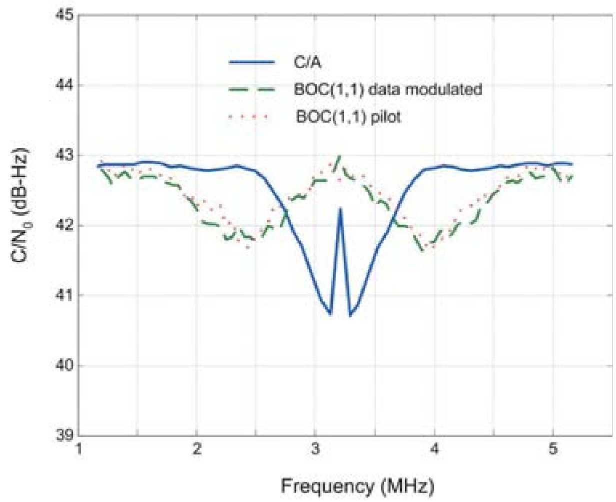

Figure 13. C/N_0 as function of jammer frequency.

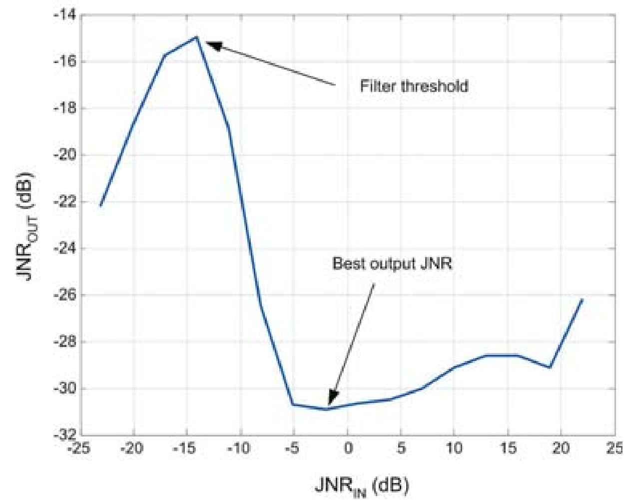

Figure 15. JNR at the output of the filter as a function of JNR at the input of the filter.

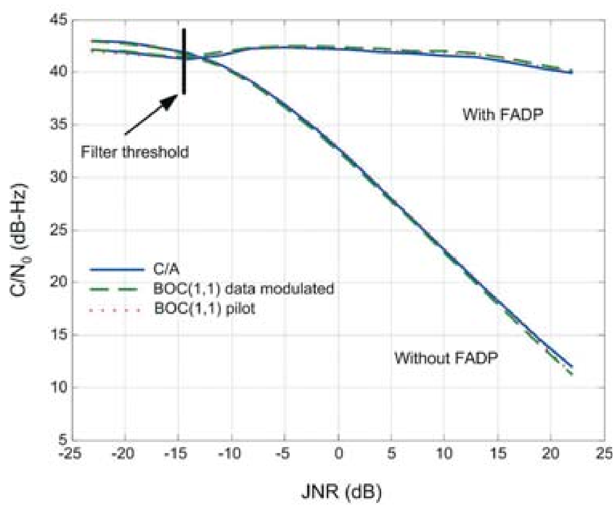

Figure 14. C/N_0 as function of jammer frequency.

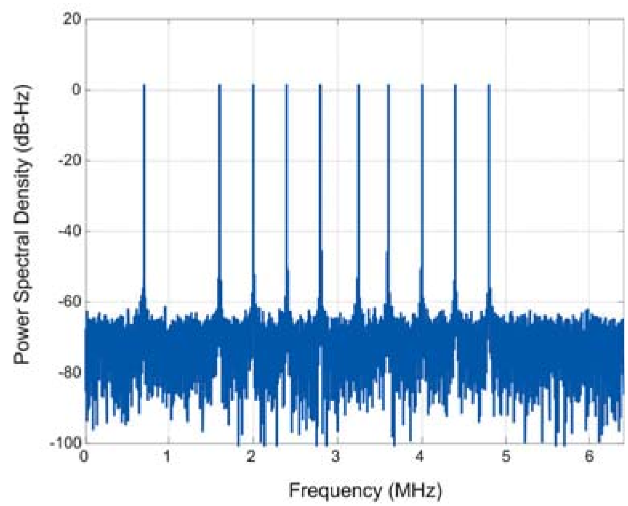

Figure 16. Spectrum of the mixed signal at the input of the FADP filter.

4. Conclusions

In this paper, a generic Matlab/Simulink® simulator for a hybrid GPS/Galileo communication channel analysis in the presence of interferences and multipath effects has been presented. As the final signal definition for the Galileo positioning system is still under consideration, the developed software simulator can be used for the design of new robust receivers. An example of this kind of receiver architecture is presented in the first part of the paper. As the simulator is designed in Simulink®, the configuration of the communication channel can be done very easily in an interactive mode. The simulator flexibility reduces the time of analysis of the signal processing allowing for control during the simulation. In the second part of the paper, an example concerning the use of the simulator is presented. For this purpose, an analysis of the vulnerability of the receiver was done in the presence of CWI jammers. The effectiveness of the simulator has been demonstrated for an anti-jamming filter analysis. Finally, the simulator has been used to estimate the positioning errors in the presence of multipath for new BOC(1,1) and C/A signals.

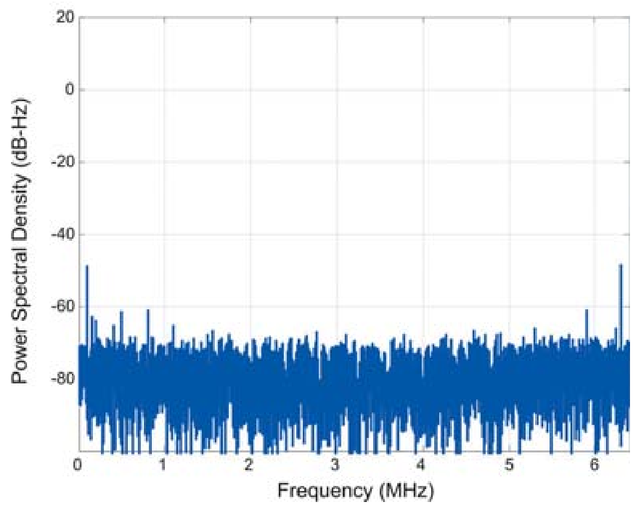

Figure 17. Spectrum of the mixed signal at the output of the FADP filter.

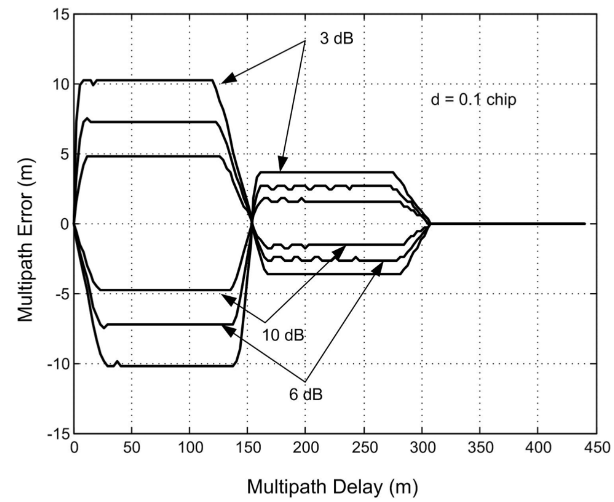

Figure 19. Multipath error for the BOC(1,1) signal as a function of the multipath signal strength.

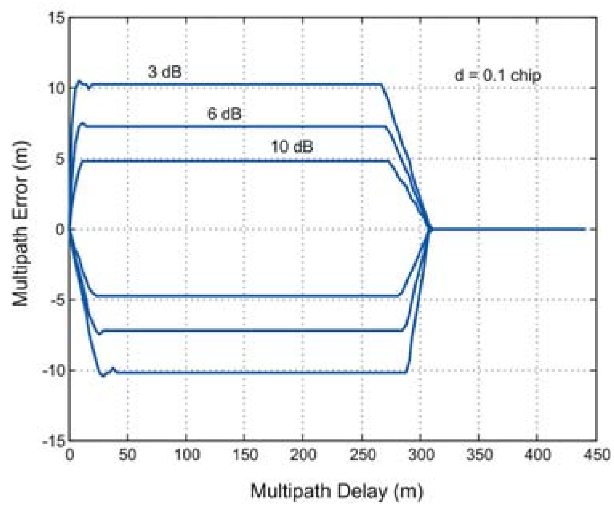

Figure 18. Multipath error for the C/A signal as a function of the multipath signal strength.

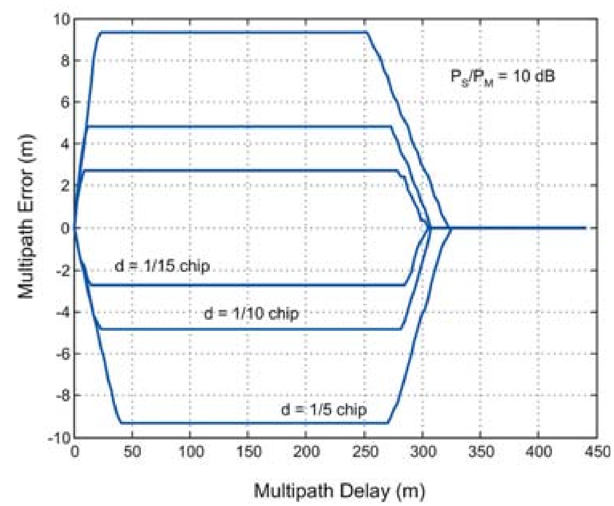

Figure 20. Multipath error for the C/A signal as a function of the correlator spacing *d*.

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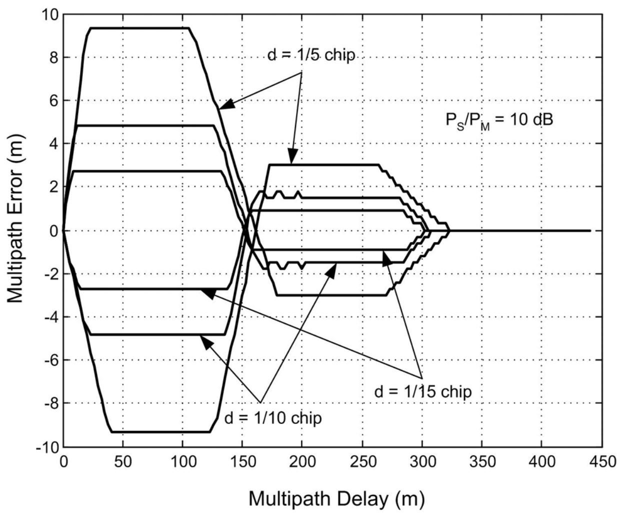

Figure 21. Multipath error for the BOC(1,1) signal as a function of the correlator spacing *d*.