Performance Evaluation and Analysis of a Hybrid Version of a Software Defined GPS/Galileo GNSS Receiver for Dynamic Scenarios

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BIOGRAPHY

Aurelian Constantinescu received an Aerospace Engineering Degree from the Polytechnic University of Bucharest (Romania) in 1992. He has received also a Master’s Degree in 1993 and a PhD in 2001 in Control from the Polytechnic National Institute of Grenoble (France). He worked as a post-doctoral researcher at the Launch Division of the French Space Agency (CNES) in Evry (France), on the control of conventional launchers and, in particular on the Ariane 5 launcher. Since 2002 he is a post-doctoral researcher in the Electrical Engineering Department of Ecole de Technologie Superieure (ETS), Montreal (Canada). His research interests in the last 2 years include Global Navigation Satellite Systems (GPS and Galileo) and Indoor Positioning Systems.

René Jr. Landry is a professor in the Electrical Engineering Department at ETS. He is active in the signal processing domain applied to the design of digital receivers, the conception of electronic devices related with satellite navigations and the non destructive evaluation in nuclear applications (EPRI). He has 2 years of experience in the Canadian space industry (Spar Aerospace) before having passed 7 years of research in Europe. Member of the LACIME Groupe at ÉTS, he is the founder of 3D ÉTSNAV Laboratory working in the domain of GPS satellites Radio-Navigation for civil and military projects in terrestrial, aeronautical and space applications.

Iurie Ilie is a research engineer in the Electrical Engineering Department at Ecole de Technologie Superieure (ETS) of Montreal. He received a Radiotechnical Engineering Degree from the Radiotechnical University of Kiev in 1982 and Master's Degree in 2003 in Satellite Navigation and Signal Processing from the ETS of Montreal. He is involved in GNSS research since 2001.

ABSTRACT

This work presents an analysis of the performance improvements of the GPS/Galileo satellite navigation system using a Global Navigation Satellite System (GNSS) software simulator. The generic simulator includes the entire satellite communication system, from the satellite constellations (24 GPS and 27 Galileo satellites), disturbance channel, up to the GPS/Galileo receiver.

The Galileo satellite constellation will at least double the number of the existing GPS navigation satellites. The increased number of satellites will improve the robustness of the actual GPS satellite navigation system and will minimize also the lack of visibility of satellites in urban canyons.

An important part of this work is the analysis and the evaluation of the positioning errors obtained for two different receiver dynamic scenarios with the GPS, Galileo and the combined GPS/Galileo satellite navigation systems. Moreover, it is desirable to simulate the improvement brought by the Galileo navigation system on the existing GPS performances, by considering a variety of dynamic scenarios, at different latitudes on Earth and for different elevation masks. Precision performances of GPS, Galileo and GPS/Galileo receivers are evaluated, compared and analyzed. The GNSS software simulator considered may use almanac information to determine satellite availability at different locations and at different instants.

Positioning errors obtained with only GPS and only Galileo navigation systems are evaluated and compared to the ones obtained with the combined GPS/Galileo navigation system. The simulation results show a positioning improvement by using the hybrid receiver (both GPS and Galileo constellations) in both dynamic scenarios considered in this paper. The use of the hybrid GPS/Galileo system improves the positioning error of at least 21% compared to only GPS and 42% compared to only Galileo.

Analyses are performed with respect to visibility, Horizontal Dilution of Precision (HDOP) and Vertical Dilution of Precision (VDOP) parameters in order to obtain a better understanding of the results obtained from the position estimates.

1. INTRODUCTION

The advent of the European Galileo navigation system and the modernization of the American GPS will lead to an improved GNSS. The Galileo system provides a lot of potential for innovative developments like the possibilities of hybrid architectures design (e.g. hybrid GPS/GALILEO receivers, use of new concepts like Software Defined Navigator, etc.).

Software receivers are very valuable in evaluating potential improvements because of their flexibility. A GNSS software simulator has been developed at Ecole de Technologie Superieure of Montreal on the basis of Matlab/Simulink, including the entire satellite positioning system: GPS and Galileo constellations with the corresponding satellite signals generation, disturbance and propagation channel (including the thermal noise, multipath, Doppler, jammers, ionospheric and tropospheric delays, etc.) and hybrid GPS/Galileo receiver. The simulator is used for an analysis of the performance improvements brought by the European Galileo system. It allows simulating a completely digital architecture of GPS, Galileo and hybrid GPS/Galileo receivers and it ensures also flexibility and interactivity during the simulations.

The Galileo satellite constellation will at least double the number of the existing GPS navigation satellites. The increased number of satellites will improve the robustness of the actual GPS satellite navigation system and will minimize also the lack of satellite visibility in urban canyons. In our implementation, the architectures of GPS and Galileo are based on 24 and 27 satellites, respectively, but almanac information may be also considered in order to determine satellite availability at different locations and at different instants.

The constellation parameters used in this paper and a thorough analysis of the improvement brought by the Galileo constellation are presented in Constantinescu *et al.* [2004]. Research results have shown that the civil navigation receiver design should be done in the E2-E1-L1 frequency band, as both systems (GPS and Galileo) use the same carrier frequency (Hein *et al.* [2001] and Ilie [2003]).

In this paper, a brief review of the different approaches considered in the literature is presented, in order to better situate the present approach. A presentation of the evaluation parameters (position error, availability, accuracy) is also done. A brief description of the European Galileo system as well as the GPS and Galileo satellite constellations parameters are presented in Section 2. The signal structures and parameters of the GPS and Galileo systems are reviewed in Section 3. The description of the SDN (Software Defined Navigator) hybrid GPS/Galileo simulator used in this paper as well as its main functionalities are presented in Section 4.

In order to evaluate and analyze the positioning errors obtained for various receiver dynamic scenarios with the GPS, Galileo and the combined GPS/Galileo satellite navigation systems, performance evaluation parameters are considered. A description of these parameters is done in Section 5.

Simulation results for two different dynamic scenarios are presented and analyzed in Section 6. Positioning improvements may be seen when using the hybrid GPS/Galileo receiver in both dynamic scenarios considered: circular and helical. The improvement brought by the hybrid system is quantified and the results are detailed. For this work, C/A-code signal has been considered for GPS and BOC(1,1) for Galileo (both signals use the same carrier frequency in the band E2-L1-E1 and the same type of discriminator may be used in both cases). Nevertheless, research is in progress for designing better discriminators for the Galileo signals, in order to improve the accuracy of the system. 52 dB C/N_0 ratios have been considered. The results obtained show an improvement in positioning when both systems, GPS and Galileo are used. Due to the simulation time of the tests, the receiver has been used in “hot start” mode, but the GNSS software simulator allows also performing in “cold start” mode.

Real and estimated positions are compared for both trajectories and the corresponding mean errors and error standard deviations are presented. Analyses are performed with respect to visibility, Horizontal Dilution of Precision (HDOP) and Vertical Dilution of Precision (VDOP) parameters in order to obtain a better understanding of the results from the position estimates.

The paper has several contributions on the gain that can be achieved using the European Galileo Satellite Navigation System. One can see that the use of the combined GPS/Galileo system provides a better availability for positioning in high elevation masking conditions (e.g. urban environments) than the GPS system alone, as well as better accuracies.

A number of papers have been dedicated to the study of the hybrid GPS/Galileo satellite navigation systems, especially to the gain brought by the hybrid receivers. Thorough analyses of the hybrid GPS/Galileo constellations are presented in Constantinescu *et al.* [2004], O'Keefe [2001], O'Keefe *et al.* [2002], Tiberius *et al.* [2002], Verhagen [2002] and Wu *et al.* [2003.]

Different approaches for GPS Receiver Design have been presented in the literature. An IF (Intermediate Frequency) Software GPS Receiver and the results obtained are very well detailed and analyzed in Krumvieda *et al.* [2001]. A modular re-programmable digital and software based GPS receiver architecture that can be easily and cost-effectively adapted for a variety of advanced GPS applications is presented in Holm *et al.* [1998]. In Ries *et al.* [2002a], a software receiver is presented for the new L5 GPS signal. Finally, in Dennis [1997], a software approach to a GNSS receiver design is presented.

2. EUROPEAN SYSTEM GALILEO VS GPS

2.1. Galileo Project

The European Global Navigation Satellite System, Galileo, consists in 30 Medium Earth Orbit (MEO) satellites and the associated ground infrastructure. Galileo is a civil controlled system managed by the Commission of the European Union (CEU) and the European Space Agency (ESA). Galileo is an independent system, but interoperable with GPS. The deployment of Galileo as a second, independent and interoperable satellite navigation system will bring an increase of the navigation consumer market. In comparison to GPS, which provides 2 services with higher and lower precision (C/A-code and P-code), Galileo provides several services in terms of accuracy, service guarantee, integrity, and other parameters. For more details see Onidi [2002], European Commission [2002] and European Commission & ESA [2002].

Several approaches have been considered in the literature concerning the design of the Galileo satellite constellation. Hence, different types of constellation have been proposed, mainly based on combinations of MEO and GEO (Geostationary) satellites (Lucas and Ludwig [1999], Tytgat and Owen [2000], Ryan and Lachapelle [2000], Oehler *et al.* [2000] and O'Keefe *et al.* [2002]).

A number of studies concerning the compatibility and interoperability of the 2 satellite navigation systems, GPS and Galileo and the problems of sharing GPS frequency bands with Galileo have been presented in the literature (Turner *et al.* [2003], Dafesh *et al.* [2002], Hein *et al.* [2001] and Godet [2000]).

For more information on the European Galileo system see also Tytgat and Owen [2000], Breeuwer *et al.* [2002], European Commission [2002] and Onidi [2002].

2.2. GPS Constellation Parameters

The GPS constellation comprises 24 satellites situated 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^o 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. For more information about the GPS constellation parameters see Parkinson and Spilker [1996], Kaplan [1996] and Constantinescu *et al.* [2004].

2.3. Galileo Constellation Parameters

The space segment of Galileo consists of 27 MEO satellites, distributed over 3 orbital planes (named A through C) with a radius of the orbits of 29600.318 km and a period of 14 h 21 min (3/5 of the mean sidereal day). The inclination of the orbits is 56^o relative to the equatorial plane (9 satellites per orbit, named 1 through 9). The satellite planes are equally spaced in longitude relative to the vernal equinox, and the satellites in each plane are also equally spaced. For more information about the Galileo constellation parameters see Constantinescu *et al.* [2004] and ESTEC [2004].

3. BASIS OF GPS AND GALILEO SIGNALS

Multiple frequency transmissions represent the near future of the civil satellite navigation systems. The current civil GPS signal has been designated as L1 and it consists of a single frequency transmission at 1575.42 MHz. 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. A third civil frequency signal is scheduled also in the future (the first launch is scheduled for 2005 and the full operational availability around 2012), at 1176.45 MHz and designated L5. So currently, GPS transmits on the L1 and L2 frequencies, but future GPS satellites will transmit also on the L5 frequency.

For more details on the future GPS signals and the associated advantages see Fontana *et al.* [2001], Van Dierendonck *et al.* [2001], Van Dierendonck and Hegarty [2000] and Ries *et al.* [2002a].

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 evolution of the GPS and Galileo signals is presented in **Figure 1**.

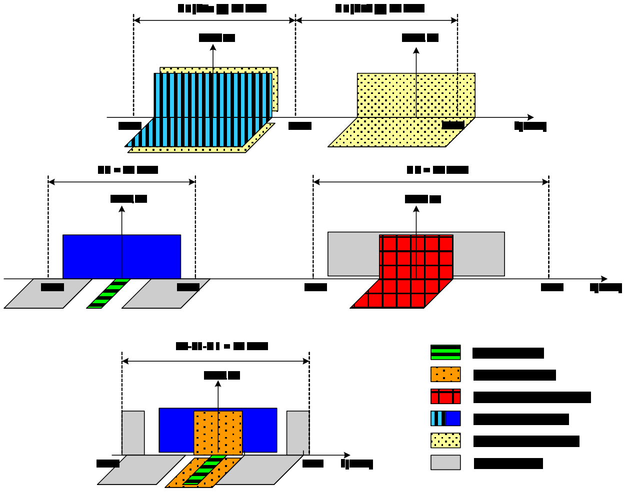

Figure 1: Evolution of GPS and Galileo signals

The signal plan for Galileo has been presented in Hein *et al.* [2001] and Hein *et al.* [2002]. In the latter, the Galileo carrier frequency, modulation scheme and data rate for all 10 navigation signals are also presented.

An overview of the actual and future GPS and Galileo signals and the corresponding frequencies are given in **Table 1**.

System	**Signal**	**Frequency** [MHz]	**Frequency** [x10.23MHz]
GPS	L1	1575.420	154
	L2	1227.600	120
	L5	1176.450	115
Galileo	E1	1575.420	154
	E5a	1176.450	115
	E5b	1202.025	117.5
	E6	1278.75	125

Table 1: Overview of available and future GPS and Galileo signals

For further details on the Galileo BOC signals see Ries *et al.* [2002b].

4. SDN SIMULATOR

At the origin of the design of the SDN Software Simulator is a generic GPS receiver architecture largely approached in the literature (Kaplan [1996]). A thorough analysis of the GPS and Galileo receivers architecture is presented in Ilie [2003], as well as some anti-jamming and multipath analysis in Ilie and Landry [2003].

The development environment used for the SDN GPS/Galileo Software Simulator is Matlab/Simulink. It allows fast implementation, easy signal processing and graphical representation. In addition, the simulator may be controlled via Matlab Web Server, which allows remote parameters configurations, simulations and results analysis.

Among various objectives of the simulator, the following ones are very important: (a) Evaluation of new signal processing techniques for the new Galileo signal structure; (b) Receiver design for receiver hardware implementation and signal processing. The simulator has two main features: (a) GPS/Galileo satellite constellation simulator and receiver trajectories generation (navigation) – Microsoft Flight Simulator or X-Plane simulated trajectories may be also used; (b) GPS/Galileo signal simulator and the corresponding signal processing algorithms.

While the Galileo signal definitions were not completely approved, the definition of a software defined navigator was the ideal way for receiver design. The fact that the two satellite navigation systems (GPS and Galileo) will share two carrier frequencies in the L1/E2-L1-E1 and L5/E5a bands (see Hein *et al.* [2001], Hein *et al.* [2002], Ilie [2003] and Ilie and Landry [2003]) simplifies the architecture of the possible hybrid receivers and opens the way to the research of new mixed GPS/Galileo architectures.

The L1 and E2-L1-E1 frequencies have been considered in the SDN simulator for GPS and Galileo, respectively. The C/A code has been considered for GPS, while for Galileo has been used the BOC(1,1) signal as well as the hexaphase modulation. As the final Galileo codes are not yet available, GPS-type codes have been used also for the Galileo system.

The structure of the SDN Simulator is presented in **Figure 2** and it consists in the following 6 main parts: (1) GPS and Galileo Satellite Constellations generation; (2) Receiver Trajectory generation; (3) GPS and Galileo signals generation; (4) Propagation and Disturbance Channel (thermal noise, multipath, jammers, ionospheric and tropospheric delays); (5) GPS and Galileo Receiver Channels; (6) Navigation Algorithm for the navigation solution computation (Position, Velocity, Time).

The position of the satellites is given to the Navigation Algorithm from the GPS and Galileo Satellite Constellation computation, but in the near future it will be known by the receiver from the navigation message sent by the satellites.

The implementation of the SDN GPS/Galileo Software Simulator is based on several steps, among which: (a) Generation of GPS (C/A) and Galileo (BOC(1,1)) baseband signals in accordance with known modulation schemes (see Kaplan [1996], Hein *et al.* [2001] and Hein *et al.* [2002]); (b) GPS and Galileo Satellite Constellations generation by using either 24 GPS and 27 Galileo satellites or almanacs (for more details on the generation of the satellite constellation see Constantinescu *et al.* [2004]); (c) Dynamic disturbances (Doppler Effect) considered on the carrier and on the code directly at the Signal Source; (d) Propagation and Disturbance Channel simulation, including thermal noise, jammers, multipath, signal attenuation, ionospheric and tropospheric delays as a function of the satellites elevation; (e) GPS and Galileo Receivers, including Phase and Delay Locked Loops, Acquisition Module for a “cold start” mode and the possibility of “hot start” (for more details see Iurie [2003]); (f) Navigation Algorithm, which computes the navigation solution by using the pseudoranges and pseudovelocities given by the receiver loops and the positions of the satellites. The navigation solution consists in the estimated position, velocity and time of the receiver.

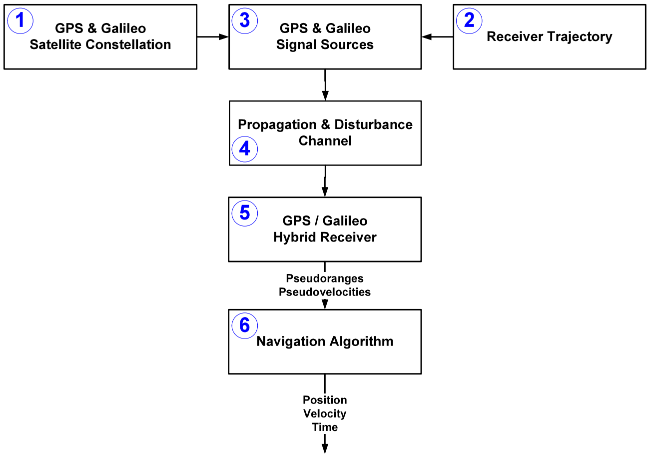

Figure 2: SDN Simulator Implementation Structure

A detailed architecture of the SDN Simulator is presented in **Figure 3**.

As it can be seen, the SDN Software Simulator has the following main characteristics:

- The receiver trajectory and the GPS and Galileo satellite constellations simulation allow the computation of the Doppler frequency on the carrier and on the code for each satellite. The satellites in visibility are chosen by using the angle of elevation of each satellite and the elevation mask considered. In order to avoid a double frequency conversion (up-conversion at the transmitter and down-conversion at the receiver), the Binary Phase Shift Keying (BPSK) modulation has been used directly on the Intermediate Frequency (IF) enabling baseband simulation.

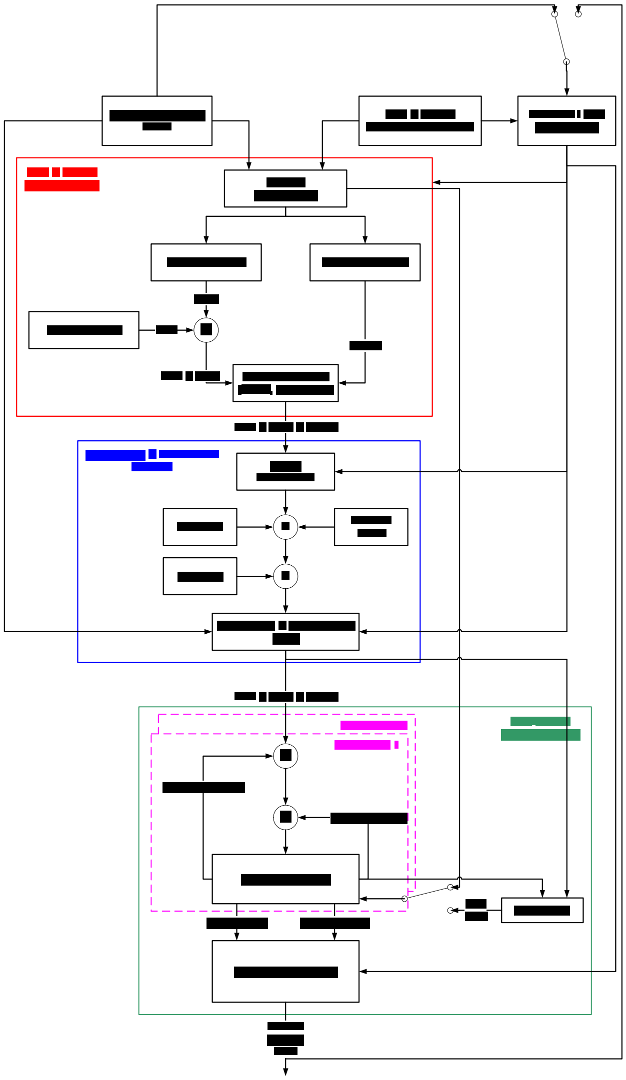

Figure 3: Detailed SDN Simulator Architecture

- Once the satellite signal simulated, the thermal noise, signal attenuation (specific to each satellite in visibility and function of the elevation angle), jammers (CWI, PWI, chirp), multipath, ionospheric and tropospheric delays (specific to each satellite in visibility and function of the elevation angle) are added in the channel block of the simulator.

- The receiver contains Phase and Delay Locked Loops (PLL and DLL) for each channel and it allows, among many other functionalities, the computation of the pseudoranges and pseudovelocities corresponding to each satellite in visibility. The simulation can be started in two different modes: (1) “Hot Start”, when the position of the satellites is considered almost known (hence the initial values of the Doppler frequency and the initial code delay may be computed by the receiver); (2) "Cold Start", when a GPS acquisition module is used in order to compute the initial values of the Doppler frequency and of the code delay.

- Once the pseudoranges and pseudovelocities computed, they are fed to the Navigation Algorithm which computes the Position, Velocity and Time of the receiver. A Kalman Filter has been designed in order to take into account a flexible number of satellites for the solution computation, being able to deal with the appearance and disappearance of satellites.

An important advantage of the SDN Simulator is that it allows the access to any signal and at any level. The models used by the simulator may be also accessed via a web site (using Matlab Web Server), which allows users to launch simulations at distance, being able to completely modify the simulator parameters.

As the SDN hybrid GPS/Galileo software simulator is quite complex, the volume of computations is important. This is the reason why the simulations presented in this paper are not very long in time. The aim of the paper is to present the methodology, implementation and feasibility of the SDN simulator and to show the improvement brought by the Galileo system. The SDN hybrid GPS/Galileo receiver is a part of an implementation methodology for the design of hardware navigation receivers using the new telecommunication SDR (Software Defined Radio) concept. The final real-time implementation will allow real-time hardware-in-the-loop positioning with the SDN hybrid GPS/Galileo receiver. For more details on the implementation methodology and capabilities of the Matlab-Simulink SDN hybrid receiver in a targeted hardware composed of a FPGA and a DSP see Dionne *et al.* [2004].

5. PERFORMANCE EVALUATION PARAMETERS

Several parameters may be used in order to evaluate the performances of the GNSS software simulator, such as positioning and velocity error, availability and accuracy.

The positioning errors represent the differences between the position solution provided by the system and the true location of the receiver, while the velocity errors are the differences between the velocity solution provided by the system and the true velocity of the receiver.

The availability concerns the number of satellites available to the user.

The accuracy is a measure of how close the navigation solution provided by the system is to the user's true location and velocity. As the distribution of the satellites in the sky is important for the accuracy of the derived user position estimate, the Dilution Of Precision (DOP) has to be computed in order to analyze the performances of the 3 different constellations: GPS, Galileo and GPS/Galileo. DOP is often used to measure the accuracy of the position of the user. The smallest DOP means the best satellite geometry for calculating the position of the user.

The accuracy of a system consists in User Equivalent Range Error (UERE) and Geometric Dilution Of Precision (GDOP).

The UERE, also known as User Range Error (URE) characterizes the effect of various errors on the pseudorange measurements. The UERE can be defined as:

$$\sigma_{\mathrm{UERE}} = \sqrt{\sigma_{\mathrm{CS}}^2 + \sigma_{\mathrm{P}}^2 + \sigma_{\mathrm{RNM}}^2},$$

where σ_{CS} is the Range Error attributed to the Control Segment, σ_{P} the Range Error due to Atmospheric Propagation and σ_{RNM} the Range Error due to Receiver Noise and Multipath.

For more details on the UERE see Parkinson and Spilker [1996] and Misra and Enge [2001].

As the DOPs are a function of the satellite-receiver geometry, the positions of the satellites determine their values. DOP values represent the geometric strength of the solution; hence, they are a good measure of the system's availability. If it is assumed that all the range measurements have the same UERE, the DOP values represent the system accuracy.

The GDOP is defined as:

$$\mathrm{GDOP} = \frac{1}{\sigma}\sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 + \sigma_b^2},$$

where σ is the measured rms error of the pseudorange (it has zero mean), σ_x, σ_y and σ_z are the measured rms errors of the user position in the x, y and z directions, respectively, and σ_b is the measured rms user clock error expressed in distance.

GDOP is the value (depending on the satellite geometry) that maps an error in the observation space (UERE) into an error in the position space (accuracy).

GDOP can be divided into 4 components: Position Dilution Of Precision (PDOP), Horizontal Dilution Of

Precision (HDOP), Vertical Dilution Of Precision (VDOP) and Time Dilution Of Precision (TDOP). These 4 components are defined as:

$$
\begin{aligned}
\text{PDOP} &= \frac{1}{\sigma}\sqrt{\sigma_x^2+\sigma_y^2+\sigma_z^2} \\
\text{HDOP} &= \frac{1}{\sigma}\sqrt{\sigma_x^2+\sigma_y^2} \\
\text{VDOP} &= \frac{1}{\sigma}\sigma_z \\
\text{TDOP} &= \frac{1}{\sigma}\sigma_b
\end{aligned}
$$

The quality of the position estimates obtained can be described as the following RMS errors:

$$
\begin{aligned}
\text{RMS 3D Posit. \& Clock Bias Estimation Error} &= \sigma\cdot\text{GDOP} \\
\text{RMS 3D Position Estimation Error} &= \sigma\cdot\text{PDOP} \\
\text{RMS Horizontal Error} &= \sigma\cdot\text{HDOP} \\
\text{RMS Vertical Error} &= \sigma\cdot\text{VDOP} \\
\text{RMSClockBiasEstimationError} &= \sigma\cdot\text{TDOP}
\end{aligned}
$$

For more details about DOPs see Misra and Enge [2001], Parkinson and Spilker [1996] and Tsui [2000].

6. SIMULATION RESULTS

The results presented in this paper have been obtained with 24 GPS and 27 Galileo satellite constellations.

Several elevation masks have been considered, but as the general conclusions are similar for the various values of the elevation mask, only results obtained with a 10^o elevation mask will be presented.

6.1. Simulations Set-Up and Receiver Scenarios

The simulations have been performed for two different receiver scenarios, the following dynamics being considered:

1. Circular Trajectory, with the following parameters: time of one complete rotation (360^o) = 60 s, radius = 1000 m. Simulation time = 30 s.
2. Helical Trajectory, with the following parameters: time of one complete rotation (360^o) = 60 s, radius = 1000 m, pitch = 5 m. Simulation time = 60 s.

For both scenarios, the receiver initial position has been considered in Montreal (45^{o}28’N, 73^{o}45’W, 31m), but tests have been performed at other locations too in order to validate the simulator. The start time of the simulation of both simulations is August20th, 2004, 00:00:00 GMT. For some results concerning the hybrid GPS/Galileo satellite constellation used by the simulator see Constantinescu *et al.* [2004].

The duration of the simulations is not too long, because of the complexity of the simulator that requires a lot of computational resources.

For both trajectories, an elevation mask of 10^o has been considered. 6 GPS and 6 Galileo satellites in visibility have been used, the various parameters of DOP (mean values over the simulation time – DOP values have very low variation as the number of satellites doesn’t change and the simulation time is quite short) being presented in **Table 2**, in function of the constellation considered (GPS, Galileo or GPS/Galileo):

Constellation	GPS	Galileo	GPS&Galileo
No. Visible Satellites	6	6	12
GDOP	2.7455	3.4339	2.0146
PDOP	2.3996	2.8471	1.7200
HDOP	1.5607	1.3059	0.9534
VDOP	1.8228	2.5299	1.4315
TDOP	1.3340	1.9198	1.0489

Table 2: Mean values of various DOPs (Circular and Helical Trajectories)

The values of the various DOPs obtained for only GPS, only Galileo and for the hybrid GPS/Galileo system show that better results from the positioning point of view should be expected when using the hybrid constellation.

In Section 6.2 will be presented the positioning results obtained for both receiver trajectories presented in this section. For each type of trajectory, 3 different results are presented: (a) estimated position using only the GPS receiver; (b) estimated position using only the Galileo receiver; (a) estimated position using the hybrid GPS/Galileo receiver. In all the situations, 12 signals sources have been considered in the simulator, 6 GPS and 6 Galileo.

6.2. Simulations Results and Analysis

The simulation results obtained by simulating the receiver trajectories described in Section 6.1 are presented in this section. An example of the data transmitted and received for one satellite is presented in **Figure 4**. A typical pseudorange error is presented in **Figure 5**.

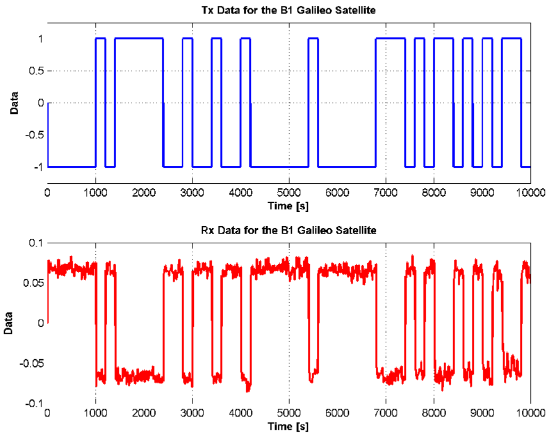

Figure 4: Data transmitted and received

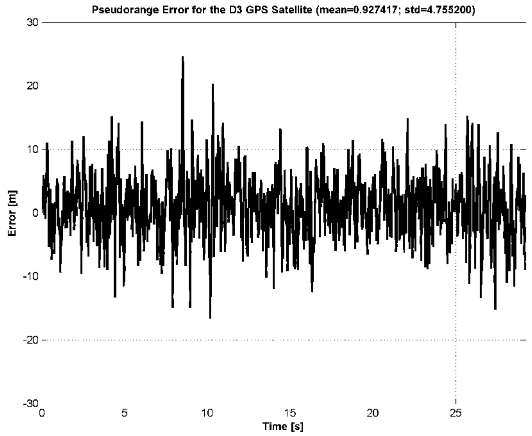

Figure 5: Pseudorange error

6.2.1. Circular Trajectory

The mean pseudorange error values and the corresponding mean standard deviations for the GPS and Galileo satellites are presented in **Table 3**.

Constellation	GPS	Galileo
Mean Error [m]	1.69	1.08
Mean StD [m]	5.51	6.72

Table 3: Pseudorange error mean values and mean standard deviations for GPS and Galileo satellites

Remark 1: One reason for the bias on the mean values of the pseudorange errors is the synchronization of all the source signals of the simulator. Tests have been done with more realistic models for the signal sources (non synchronous signals) and the bias on the mean error values is smaller.

After solving the navigation equations by using the navigation algorithm for the circular trajectory, the mean x, y and z-axis errors and the corresponding standard deviations for the GPS, Galileo and GPS/Galileo receivers are presented in **Table 4**.

Constel..	Mean Error [m]			Standard Deviation [m]		
	X	Y	Z	X	Y	Z
GPS	-1.66	-0.95	-5.20	4.59	8.73	9.00
Galileo	-2.04	-2.05	-0.12	6.49	11.62	13.49
GPS/Gal	-1.83	-0.93	-3.08	3.47	6.70	7.30

Table 4: x, y and z-axis error mean values and standard deviations for GPS, Galileo and GPS/Galileo receivers

Remark 2: As the Galileo correlator used is a C/A-type correlator, the standard deviations for the BOC signal are important. Work is in progress to improve these results by developing new Galileo correlators.

The positioning errors on x, y and z-axis for the hybrid GPS/Galileo receiver are presented in **Figure 6**, **Figure 7** and **Figure 8**, respectively.

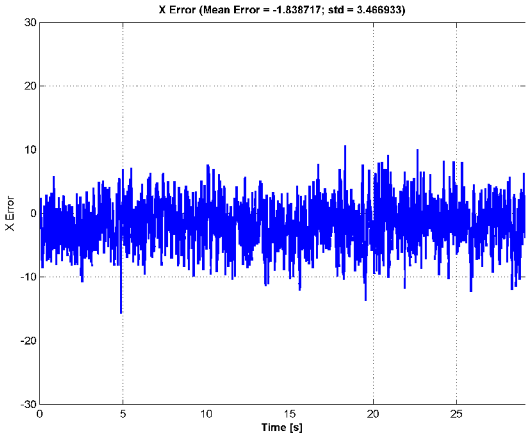

Figure 6: x-axis positioning error for circular trajectory (GPS/Galileo)

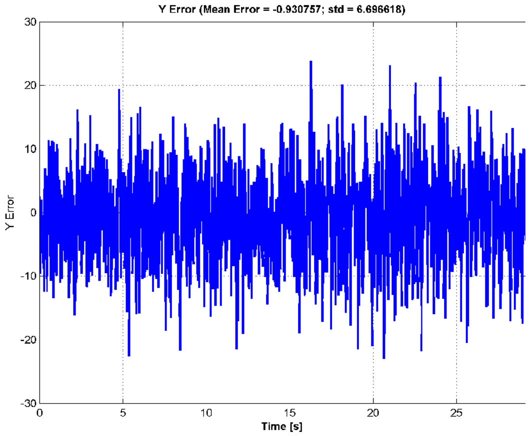

Figure 7: y-axis positioning error for circular trajectory (GPS/Galileo)

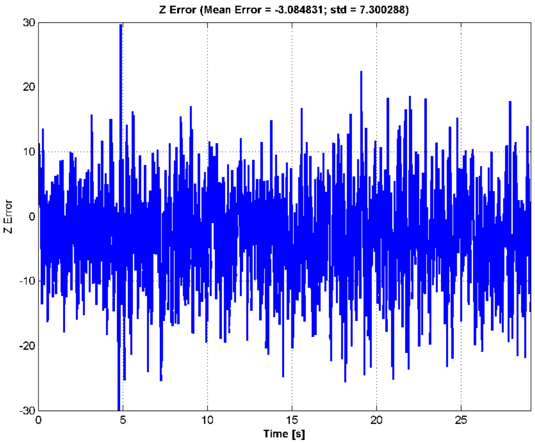

Figure 8: z-axis positioning error for circular trajectory (GPS/Galileo)

The real and estimated trajectories obtained with the hybrid GPS/Galileo receiver are presented in **Figure 9**.

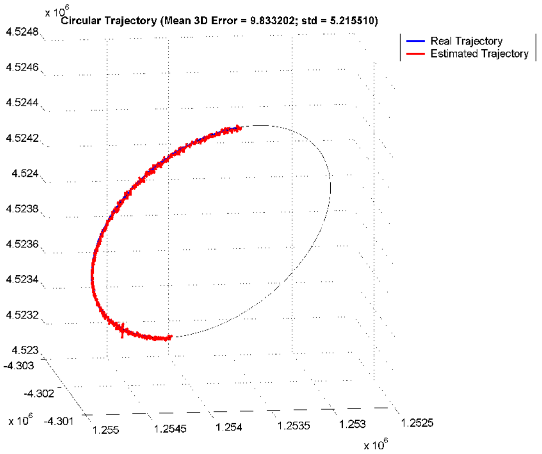

Figure 9: Real and estimated GPS/Galileo receiver trajectories for circular trajectory

The positioning x, y and z errors as well as the 3D error obtained with only GPS and only Galileo receivers are not presented, as they are quite similar.

The mean 3D errors and standard deviations for the GPS, Galileo and GPS/Galileo receivers are presented in **Table 5**. The 3D mean errors are important due to the values of the standard deviations of the x, y and z-axis errors.

Constellation	3D Mean Error [m]	3D Standard Deviation [m]
GPS	12.50	7.24
Galileo	16.86	9.12
GPS/Galileo	9.83	5.22

Table 5: 3D error mean values and standard deviations for GPS, Galileo and GPS/Galileo receivers

The results obtained show that the use of the hybrid GPS/Galileo system improves the performances of the only GPS or only Galileo systems, from the positioning point of view (as expected from the various DOP values presented in **Table 2**). The mean value and the standard deviation of the 3D error are smaller for the hybrid GPS/Galileo system than for the GPS or Galileo systems alone. The 3D mean value error has been improved by 21% and 42% with respect to the GPS and Galileo ones, respectively. The improvements of the standard deviation of the 3D error are of 28% and 43% with respect to the GPS and Galileo ones, respectively. It can be seen also that the GPS system provides better results in this case, as it could be expected from the DOP values presented in **Table 2**.

6.2.2. Helical Trajectory

The mean pseudorange error values and the corresponding mean standard deviations for the GPS and Galileo satellites are presented in **Table 6**.

Constellation	GPS	Galileo
Mean Error [m]	1.60	1.11
Mean StD [m]	5.44	6.74

Table 6: Pseudorange error mean values and mean standard deviations for GPS and Galileo satellites

The remarks 1 and 2 presented in Section 6.2.1 are also available for the case of the helical trajectory.

After solving the navigation equations by using the navigation algorithm for the helical trajectory, the mean x, y and z-axis errors and the corresponding standard deviations for the GPS, Galileo and GPS/Galileo receivers are presented in **Table 7**.

Constel.	Mean Error [m]			Standard Deviation [m]		
	X	Y	Z	X	Y	Z
GPS	-1.78	-0.68	-4.49	4.66	8.98	8.61
Galileo	-2.43	-1.22	-0.76	6.38	11.49	13.61
GPS/Gal	-1.99	-0.64	-2.82	3.47	6.80	7.37

Table 7: x, y and z-axis error mean values and standard deviations for GPS, Galileo and GPS/Galileo receivers

The positioning errors on x, y and z-axis for the GPS/Galileo receiver are presented in **Figure 10**, **Figure 11** and **Figure 12**, respectively.

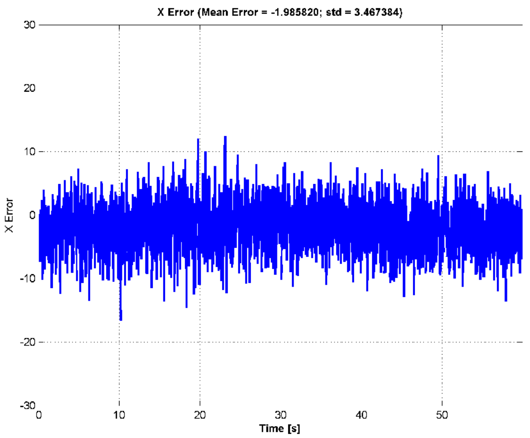

Figure 10: x-axis positioning error for helical trajectory (GPS/Galileo)

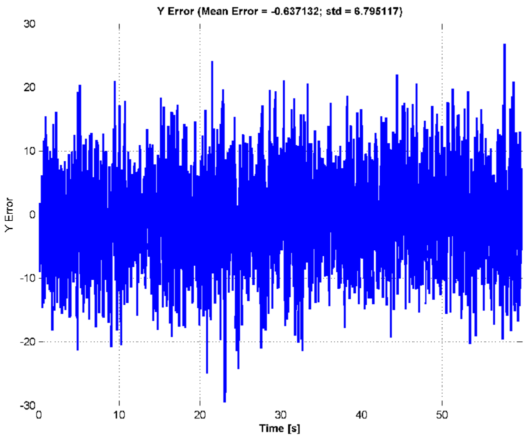

Figure 11: y-axis positioning error for helical trajectory (GPS/Galileo)

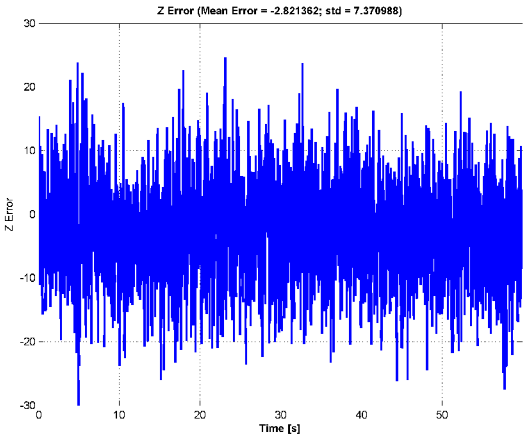

Figure 12: z-axis positioning error for helical trajectory (GPS/Galileo)

The real and estimated trajectories obtained with the hybrid GPS/Galileo receiver are presented in **Figure 13**.

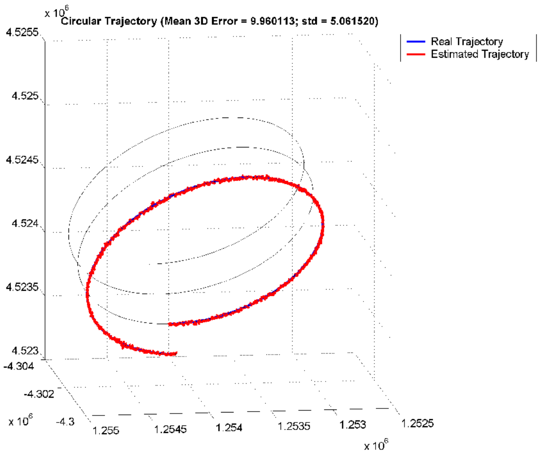

Figure 13: Real and estimated GPS/Galileo receiver trajectories for helical trajectory

The positioning x, y and z errors as well as the 3D error obtained with only GPS and only Galileo receivers are not presented, as they are quite similar.

The mean 3D errors and standard deviations for the GPS, Galileo and GPS/Galileo receivers are presented in **Table 8**. The 3D mean errors are important due to the values of the standard deviations of the x, y and z-axis errors.

Constellation	3D Mean Error [m]	3D Standard Deviation [m]
GPS	12.56	6.52
Galileo	16.77	9.21
GPS/Galileo	9.96	5.06

Table 8: 3D error mean values and standard deviations for GPS, Galileo and GPS/Galileo receivers

The results obtained in the case of the helical trajectory of the receiver are quite similar to the ones obtained for the circular one. The hybrid GPS/Galileo system clearly improves the performances of the only GPS or only Galileo systems, from the positioning point of view. The mean value and the standard deviation of the 3D error are smaller for the hybrid GPS/Galileo system than for the GPS or Galileo systems alone. The mean value and the standard deviation of the 3D error improvements with respect to GPS and Galileo systems are similar to the circular trajectory case. It can be seen also, as in the case of the circular trajectory, that the GPS system provides better results in this case, as it could be expected from the DOP values presented in **Table 2**.

7. CONCLUSIONS

This paper describes the SDN Software Hybrid GPS/Galileo Simulator. The functionalities and the implementation of the simulator have been presented, as well as the results obtained for two different dynamic receiver scenarios.

The performance improvement obtained using a hybrid GPS/Galileo satellite positioning system is evaluated and the results obtained are compared to the corresponding results obtained for the GPS and Galileo systems only. The benefits brought by the use of the hybrid constellation are presented and analyzed.

Simulated availability, accuracy and positioning errors have been presented for the three satellite navigation system configurations: GPS, Galileo and hybrid GPS/Galileo. The benefits of the hybrid GPS/Galileo system are obvious and they have been quantified in the paper. It is shown that an integrated use of the European satellite navigation system Galileo will improve the capability of positioning.

The use of the hybrid GNSS is advantageous for both dynamic scenarios presented in the paper. Positioning errors obtained with GPS or Galileo systems only have been evaluated and compared to the ones obtained with the combined GPS/Galileo navigation system. The simulation results have shown a positioning improvement by using the hybrid GPS/Galileo receiver in both dynamic scenarios considered in this paper. The use of the hybrid GPS/Galileo system has shown positioning error improvements of at least 21% compared to GPS only and 42% compared to Galileo only.

The SDN Software Simulator used in this paper and which is a complete GNSS simulator is presently under development, work being in progress to improve these results by developing new Galileo correlators and adding much more functionality to the system (additional GPS and Galileo frequencies, GLONASS, etc.).

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