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EFFECTS OF MASKING ANGLE AND MULTIPATH ON GALILEO PERFORMANCES IN DIFFERENT ENVIRONMENTS

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Abstract

Key words: Satellite navigation system, Galileo, multipath, urban environment, ray launching

Over the past few years, many applications of satellite navigation systems have been developed. Among the wide range of applications of such systems, transportation in urban environment seems to be one of the most prominent. Hence it is important to fully and accurately characterize the receiver performance for this application.
The urban environment is characterized by high masking angles and the presence of a great number of obstacles which produce multipath. Investigating the receiver performance in this medium requires a model of the wave propagation. In this paper, a ray launching simulation tool is used to characterize different environments and the receiver errors due to multipath and the receiver performance with and without augmentation are evaluated.

Introduction

Applications of satellites navigation system are expending rapidly. Europe has initiated the Galileo program, targeting the implementation of a navigation system independent and interoperable with GPS and Glonass. The architecture of Galileo is based on MEO constellation of 30 satellites with 3 spares at an altitude of 23616 km, with an inclination of 56°, distribute over 3 planes.
Galileo must take into account the need of a large number of applications. The requirements of an urban user may be very stringent. We may assume that an urban user needs availability greater than 90% with an accuracy better than 10 meters. However meeting the user needs generally is not an easy task since the urban medium presents quite constraining conditions which do not always enable to compute the user location at the level of accuracy required.
The first section of this paper deals with the channel model. As the wavelength is small with respect to the obstacles size, it is assumed that the signal propagation can be modeled as a ray using the geometric optic principle. Using such principle, simulation tool have been developed which computes the intersections between the rays and the facets that constitute the environment. In a second part, we study the influence of multipath on the receiver.
Finally, means to meet user performance objective are proposed. Additional sensors are considered to improve the receiver performance.

1. Channel model

Multipath propagation is almost inevitable in most satellite navigation ground applications, since there are many obstacles as buildings in the surroundings of the receiver. Several methods exist to estimate the effect of these perturbations. Methods based on statistical formulations from peculiar measurement have been disregarded since they cannot provide the required level of precision. These methods do not provide a realistic model of masking angle and multipath. Moreover, these methods are valid only for some specific type of environment, range of frequencies, etc…
Therefore, a deterministic method, based on geometrical optic, has been selected that allows to describe the environment in 3D and multipath propagation to the desired level of accuracy. It allows to simulate different transmitters and receivers, fixed or mobile.

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This simulation tool is composed of four modules.
The first one defines the characteristics of the satellite constellation, several constellations can be simulated (Walker, GEO, …).
The second module simulate the wave propagation. This module determines for each satellite the direct path and the coordinates of the signal impact on the environment surfaces.
The next module is the electromagnetic module which determines, for every path, the attenuation introduced by the reflection and the delay between the direct path and the reflected path. At each reflection, the reflection coefficient is computed according to the nature of the surface. Moreover, a reflection translates in a polarization change. For each path, the simulation tool determines the signal polarization, then the signal is decomposed in two signals polarized right hand circular and left hand circular. This allows to obtain the composite signal at the output of the receiver antenna considering antenna gain on each polarization.
The last module defines the characterization of the scene. Different parameters can be used for simulate the scene :

- Building surface
- Building height
- Street length

The simulation tool can also used VRML files to define the scene.

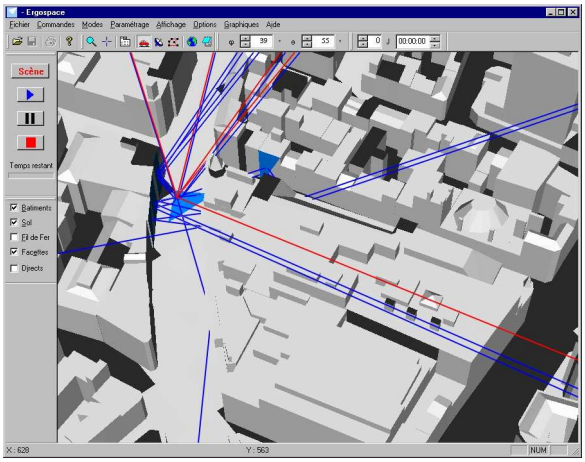

Figure 1: Simulation tool interface

Figure 1 shows the simulation tool interface with a VRML scene. In red, it is the direct path and in blue the reflected path. The facets encountered are in blue.

2. Influence of multipath on the receiver

In a navigation receiver, there is an acquisition mode and a tracking mode. In this paper, it is assumed that the receiver operates in the tracking mode.
A non coherent delay lock loop is considered as the advantage of the non coherent loop with regard to the coherent loop is to avoid the need for carrier phase estimation.
Multipath is characterized by the sum of delayed echoes of the emitted signal, hence the received signal could be written as follows:

$$s_r(t) = \sum_{m=0}^{N} a_m(t)\, p(t-\tau_m(t)) \sin(2\pi f_p t + \phi_m(t))$$

Where N is the number of reflected paths, a_m the amplitude of path m, τ_m delay of path m and $\phi_m = 2\pi f_{dm} t - 2\pi f_p \tau_m$, f_{dm} is the Doppler shift of path m. In the following, the temporal dependence of the parameters are not taken into account.
The influence of multipath depends on their signal strength and delay compared to that of the line of sight signal. The delay loop induces a tracking error on direct path delay estimation called «code offset».

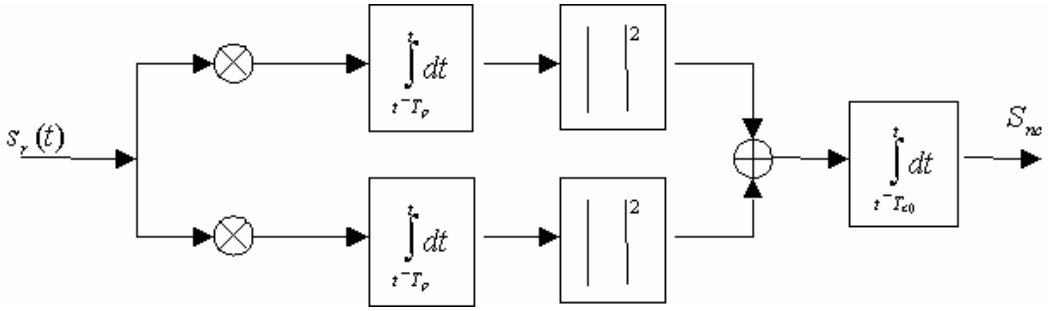

Figure 2: Non coherent delay lock loop phase detector

In a non coherent DLL, the S curve is obtained by subtracting the squared early and late responses:

$$S_{nc}(\hat{\tau}_0) = \int_{t-T_{c0}}^{t} \left[\left| \sum_{m=0}^{M} a_m R(\hat{\tau}_0 - \tau_m + d/2) e^{j\phi_m} \right|^2 - \left| \sum_{m=0}^{M} a_m R(\hat{\tau}_0 - \tau_m - d/2) e^{j\phi_m} \right|^2 \right] dt$$

where :

- $R(\tau)$ is the correlation function of the code $p(t)$, correlated over a period of T_p seconds.
- d is the early-late spacing $d = T_c$ where T_c is the code period
- $\hat{\tau}_0$ is the estimate of the receiver line of sight delay τ_0. The one-sided noise bandwidth $1/2T_{c0}$ of the averaging operation is referred to as the tracking loop bandwidth B_L.

To understand the effects of multipath on the code tracking, it is important to consider two situations:

- The fading bandwidth B_F is larger than the tracking loop bandwidth B_L: fast fading
- The fading bandwidth B_F is smaller than the tracking loop bandwidth B_L: slow fading

2.1. Fast fading

If B_F is large compared with B_L, all cross products are filtered out because of their relatively high frequencies, so the resulting S-curve is simply the summation of M+1 different non coherent DLL S curves.

$$S_{nc}(\hat{\tau}_0) = \sum_{m=0}^{M} \left[\left(a_m R(\hat{\tau}_0 - \tau_m + d/2) \right)^2 - \left(a_m R(\hat{\tau}_0 - \tau_m - d/2) \right)^2 \right]$$

2.2. Slow fading

If B_F is small compared with B_L, then the averaging over T_{c0} seconds has no influence on the resulting multipath tracking errors.

$$S_{nc}(\hat{\tau}_0) = \left| \sum_{m=0}^{M} a_m R(\hat{\tau}_0 - \tau_m + d/2) e^{j\phi_m} \right|^2 - \left| \sum_{m=0}^{M} a_m R(\hat{\tau}_0 - \tau_m - d/2) e^{j\phi_m} \right|^2$$

In the case of one reflected path (M=1), maximum delay errors occur if the reflected path has a phase difference of 0 or pi radians with the line of sight path. This could observed in Figure 3.

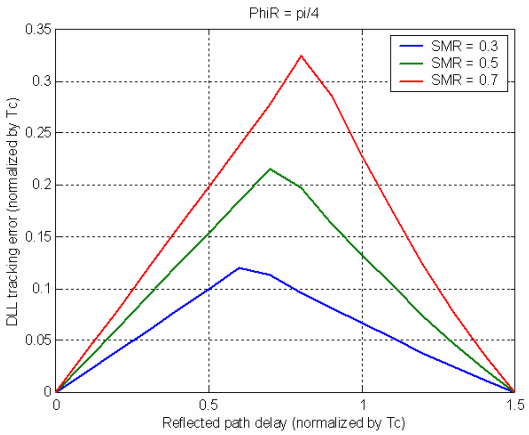

Figure 3: Multipath tracking errors function of SMR

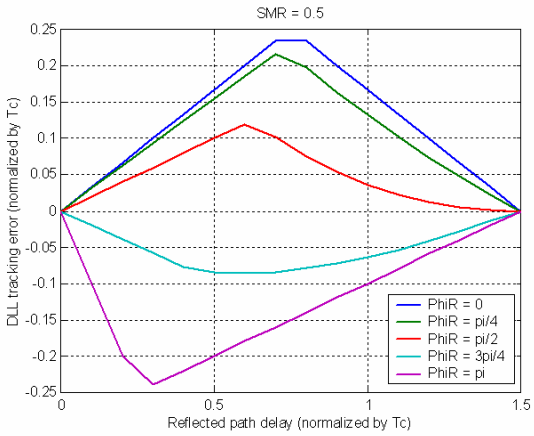

Figure 4: Multipath tracking errors function of PhiR

Figure 3 presents multipath tracking errors functions of different parameters, where $SMR = a_1/a_0$ (multipath amplitude to signal amplitude ratio), $TauR = \tau_1 - \tau_0$, $PhiR = \phi_1 - \phi_0$.

Ones can note that the higher SMR, the larger the code offset is. On the other hand if the delay between the reflected path and the direct path is small, the code offset is low. So, if considering outputs of Figure 3 and Figure 4, ones could expect that the multipath tracking error will be not very large.

The system performance in the different environments is now evaluated.

3. Performance measurement for different environments

3.1. Measurement results

These measurements were performed in collaboration with ENAC (Ecole Nationale de l'Aviation Civile). Four environments have been considered:

- Urban
- Industrial
- Residential
- High buildings with open area

The receiver has been operated in a car with a roof magnetic antenna for about an hour in each type of environment. A laptop computer recorded measurements every second, measurements being the number of GPS satellites in view.

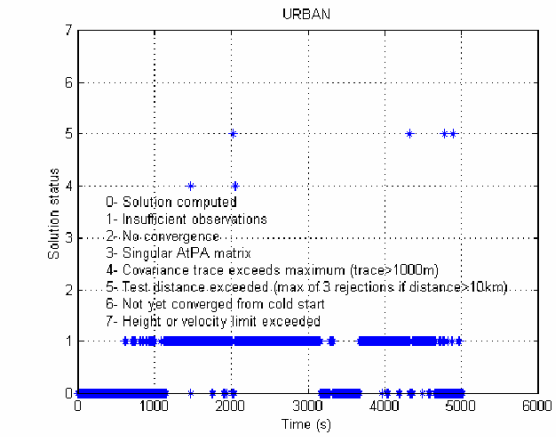

Figure 5 : Solution status in urban medium

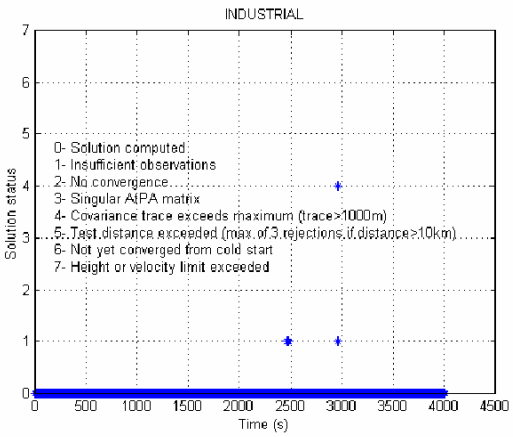

Figure 6 : Solution status in industrial medium

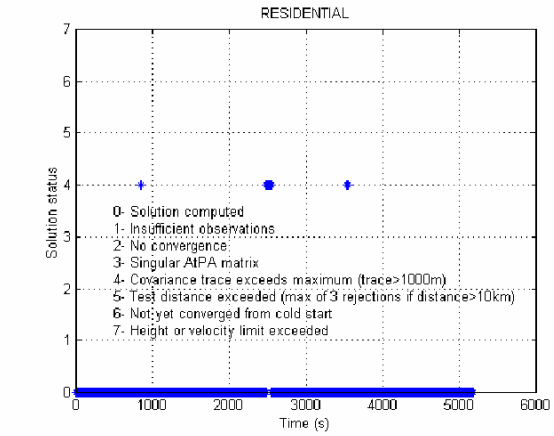

Figure 7 : Solution status in residential medium

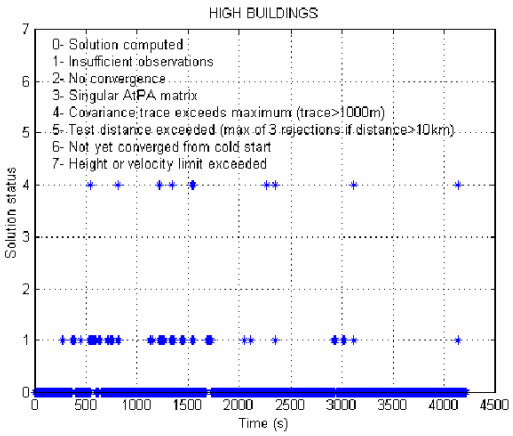

Figure 8 : Solution status in medium with high buildings

Figures 5, 6, 7, 8 present the solution status during the measurements for the different environments. A "zero" value is valid solution, a "one" corresponds to a lack of observations and value equal to "two" or above corresponds to computed solution but considered as not reliable.
In Figure 5, for urban medium, position evaluation is not often computed because of a lack of observations, and at times, the solution is not reliable because of a bad geometry of the satellites in visibility. For industrial and residential environment, visibility of the satellite is good but reliable solution are not often obtained.
In the environment composed of high buildings with open areas, the satellites are less masked than in urban medium. However when the receiver is near to a building, the satellites are masked only on a one side and as the satellite geometry is bad, the solution is not reliable.
In the next section, a comparison of visibility statistics obtained with measurement and with simulation is studied.

3.2. Measurement and simulation comparison

Visibility statistics obtained with the simulation tool are compared with measurements realized in four different environments.
The following table shows the parameters used to define the scene with the simulation tool for the different environments.

	BUILDING SURFACE		BUILDING HEIGHT		STREET LENGTH
	Width (m)	Length (m)	Mean (m)	Standard deviation (m)	(m)
Urban	20	30	25	6	20 - 25
RESIDENTIAL	11	12	6	3	7
INDUSTRIAL	21	31	8	2	19
HIGH BUILDING	25	90	30	10	45 - 60

Table 1 : Scene parameters

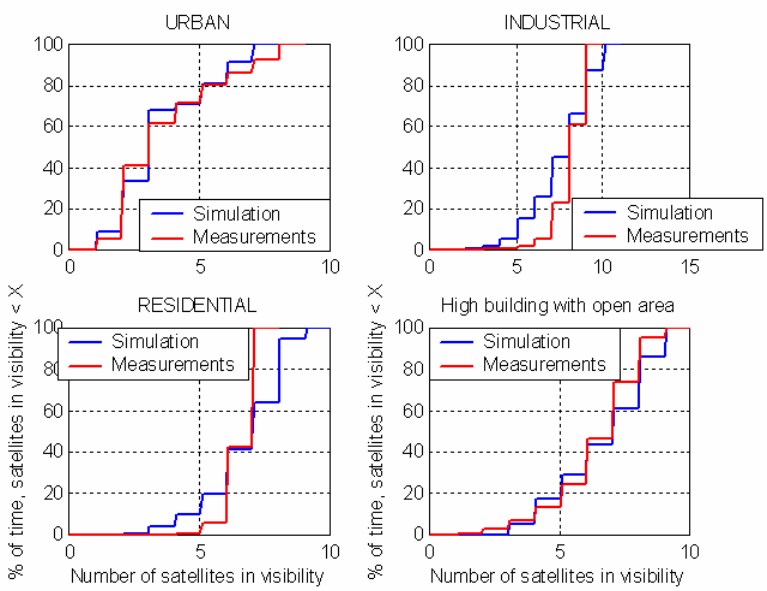

Figure 9: Comparison between measurements and simulation results

The Figure 9 presents histogram against the number of satellite in visibility. It compares actual measurements performed in four different environments (thin line) and the simulations realized with the ray launching with the parameters gives in table 1 (bold line).
In the following, all results are obtained with our simulation tool.
Statistics on multipath, considering the Galileo constellation, are now simulated in the four environments already defined. The simulation lasts five minutes, with a sampling period of one second.
These statistics make possible to compare the different environments and to characterize the different path which reach the receiver.
In the simulations, we consider that a satellite is only visible if there is a direct path, as the receiver can not track a reflected path.

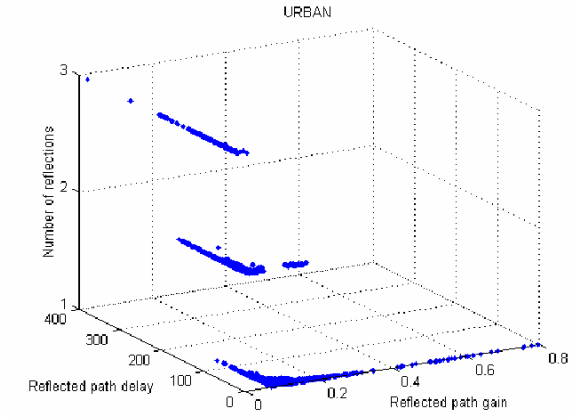

Figure 10 : Path characteristics in urban medium

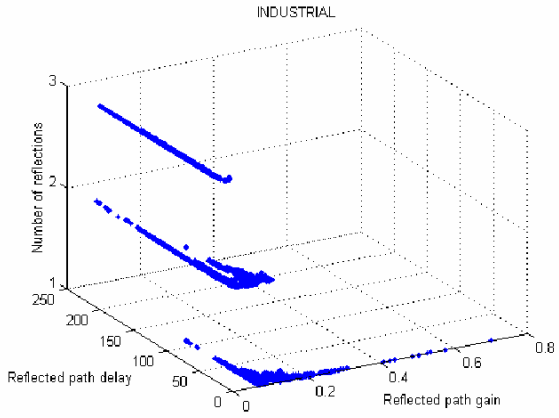

Figure 11: Path characteristics in industrial medium

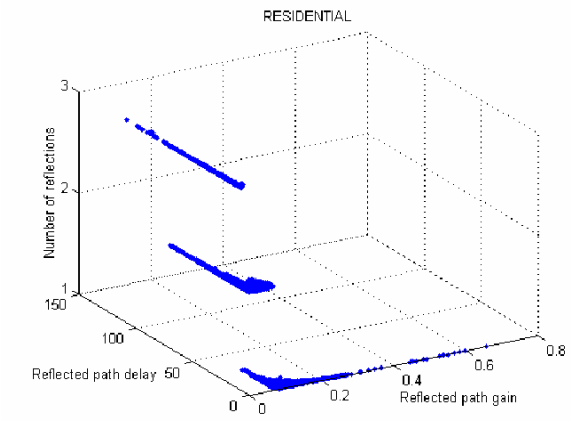

Figure 12: Path characteristics in residential medium

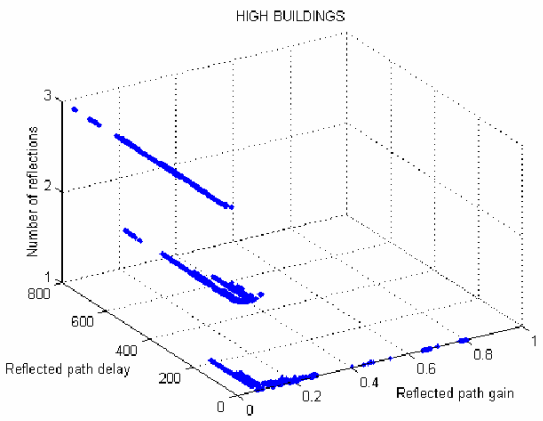

Figure 13: Path characteristics in medium with high buildings

The Figures 10, 11, 12, 13 shows the relation between the number of reflections, the gain and the delay of each reflected path for the different environments. It appears that the higher the number of reflections, the higher the delay and the attenuation on the path. It is interesting to note that in the residential environment (Figure 12), delays are shorter as the obstacles are closer from the receiver than in the other case. Moreover, for three reflections, the gain is already less than 0.1, this confirms that it is useless to consider more than three reflections.

4. Galileo performance

The carrier used in the simulations is in L band, near L1 GPS frequency, and is right hand circular polarized. The signal has a rectangular wave form with a chip rate of 1.023 MHz (it does not represent Galileo baseline but rather a standard case).
The simulations is carried out in Toulouse, France (latitude:43.62°, longitude:1.45°) and the receiver is moving at a velocity of 30km/h.
Pseudo-range measurements are available, ionospheric and tropospheric correction are performed using models in the receiver.
The Kalman filtering applies on measurements. The state vector is composed of the receiver position, the receiver speed and the receiver clock error. The propagation model considers that user speed is constant.
The system performance on the user position determination is evaluated for five different cases. A comparison will be carried out with :

- Urban environment
- Industrial environment
- Residential environment
- Environment with high buildings with some open areas

The analysis focuses on the horizontal error, as vertical error has little importance for urban user.

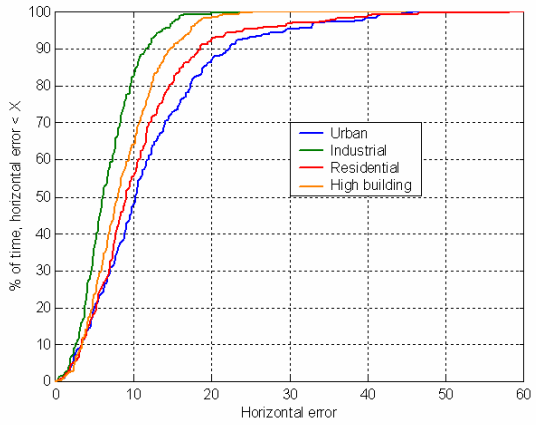

Figure 14: Percentage of time function of position error for different environments

It is assumed that the performance objectives for an urban user corresponds to an accuracy between 1 and 10 meters, with maximum availability (at least 90%).
Figure 14 shows system performance without augmentations. In the industrial environment and the environment with high building and some open area, the results are satisfactory. In the case of urban environment and of residential case, the results are worst than in the two precedent cases. More generally the performance is not sufficient in all situations. Since the stand alone system cannot provide the level of accuracy desired, several type of augmentation are to be considered to improve the system performance.

There are several approaches to improve the system performance:

- Space based augmentations : complementing the Galileo constellation by the GPS constellation
- Add additional sensors at the user level : altimeter, dead reckoning

5. Augmentations at the space segment

One approach to improve the availability of the system is to increase the number of satellites, for instance complementing the Galileo constellation with GPS constellation. We make the assumption that receiver can be used in dual mode (Galileo + GPS), with a known time bias between GPS/Galileo.

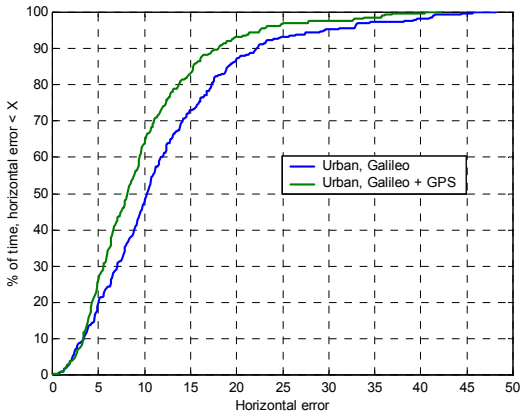

Figure 15: Percentage of time function with and without GPS

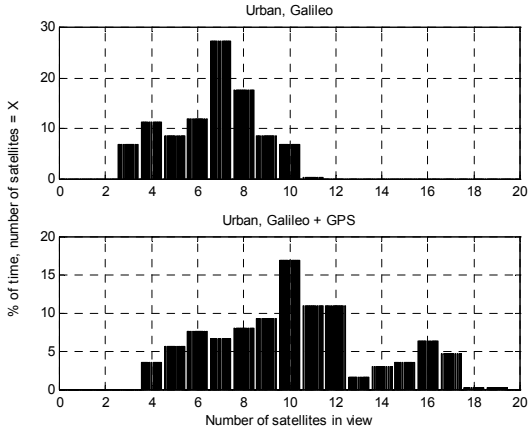

Figure 16: Number of satellite in view

Figure 15 compares the performance of the Galileo system alone and the performance of Galileo complemented by the GPS constellation. An improvement is observed but it is small. Overall the required objectives are not met.
Figure 16 shows the number of satellites in view when there is only Galileo constellation and when it is complementing by GPS constellation.

6. Galileo performance with additional sensors

The second approach to improve the system performance is to hybridize the receiver with additional sensors. Two types of sensors have been considered :

- Baro_altimeter
- Dead reckoning (sensor providing data about distance and direction) modeled as a planimetric sensor

The considered sensor impairments are a noise, a bias and a drift.
The basic idea is to use sensors when there is a lack of measurements, and to use the navigation system to recalibrate the sensors. The drawback of this solution is some complexity induced at the receiver architecture level.
The state vector of the Kalman filtering is the same than previously with addition of sensor bias. In addition of the pseudo-range, the Kalman filter uses the sensor readings.
Now, the system performance with each of the two sensors will be analyzed. In the following simulations, only the case of the urban medium is considered.

6.1. Altimeter

The first sensor considered is the baro-altimeter. In the following simulation, the sensor noise is estimated to be 0.1 meter and its bias 1 meter. Different values of drift are considered.

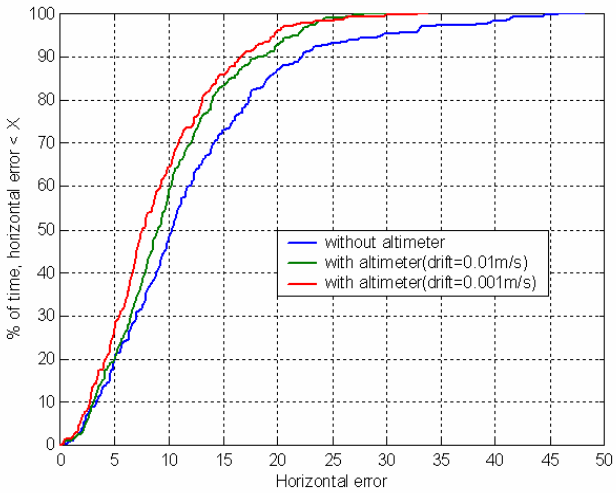

Figure 17 :Percentage of time function of position error without and with altimeter

Figure 17 presents the percentage of time function of horizontal error without augmentation and with different type of baro-altimeter. Thanks to additional measurement obtained from the sensor significant improvement of performance are obtained, in particular for the 5km/h case because of the greater lack of measurements without augmentations. Overall, the results are good but not sufficient with regard to the objectives.

6.2. Dead reckoning

The second sensor considered is dead reckoning which is modeled like a planimetric sensor.

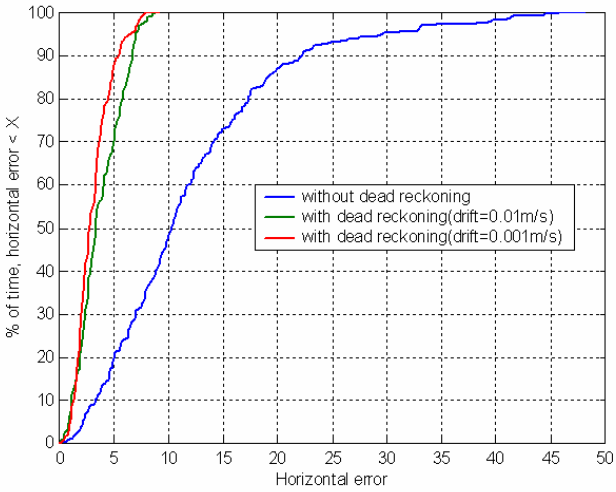

Figure 18 : Percentage of time function of position error without and with dead reckoning

Figure 18 shows the percentage of time function of position error without augmentation and with dead reckoning for different drift and noise. Whatever sensor drift have been considered, in the both case, we obtained the desired result. Of course with a sensor of best quality, the result are better, but a sensor cheaper is sufficient to fulfil the user needs while taking into account two major drivers of this study: user cost and system cost.

Conclusions

There is an increasing requirement for an accurate navigation system for urban application. Urban user needs an accuracy between 1 and 10 meters, with an availability at least 90%. The presence of multipath components in the received signal adversely affects the ability of the receiver to compute accurate navigational solutions.
The performance in stand-alone of the Galileo system in urban environment is not sufficient because of these two phenomenon, so different ways to improve performance have been considered.
The first method which consist in complementing Galileo constellation with GPS constellation, improves result but not sufficient with regard to our objectives. The second method is the hybridization with additional sensors yields very promising results.

Acknowledgements

Acknowledgments are due to Mr. Bruno Lobert and Mr. Christophe Bourga from Alcatel Space Industries for their support during this study.

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