Hybrid deterministic-statistical GPS multipath simulator for airport navigation

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Abstract

A prediction model of GPS multipath requires a constant trade-off between computation time and realistic modeling. In previous papers we have presented a GPS multipath simulator based on physical optics. Regarding the design of this deterministic model, we have carefully justified the choices we have made to obtain reasonable computation times. They concern both the electromagnetic method and the precision of the data used to describe the 3D scene. To account for the limits of these choices, we define in this paper a new statistical model and we propose an innovative hybrid deterministic-statistical GPS multipath simulator adapted to airport navigation. This hybrid simulator is based on the deterministic simulator via Monte-Carlo simulations. Its statistical origin is the variability of the environment. For a particular scene its outputs are the statistical moments of the GPS range error. We show the necessity of this statistical component for realistic prediction purposes in comparison to pure deterministic predictions by means of simulations on a test-case.

1. INTRODUCTION

For precise GPS positioning one major source of error is multipath. Therefore, in a complex environment such as an airport it is important to get information about the possible multipath signals.

In the literature we can distinguish three kinds of prediction models: deterministic models [1]-[2], statistical models [3]-[4] and finally hybrid models which mix both deterministic and statistical prediction [5]-[6]. In [7]-[8] we have presented the development of a deterministic GPS multipath prediction simulator based on physical optics (PO) adapted to airport navigation. Regarding the design of this deterministic model, we have carefully justified the choices we have made to obtain reasonable computation times. They concern both the electromagnetic prediction method and the precision of the data used to describe the 3D scene. To account for the limits of these choices, we aim at adding a complementary statistical model.

In this paper we propose a hybrid deterministic-statistical prediction simulator adapted to airport navigation based on the deterministic simulator [7]-[8] via Monte-Carlo (MC) simulations.

In Section 2 we present the principle of our deterministic prediction simulator. In Section 3 we expose the motivations for adding a statistical component to multipath prediction, and we propose a hybrid deterministic-statistical simulator. Finally, in Section 4 we discuss the results obtained with a test-case simulation.

2. DETERMINISTIC PREDICTION

In [7], the development of a deterministic prediction software has been presented. In this section we bring to mind the basis of this simulator.

2.1. General Principle

The simulator is composed of two blocks, the multipath generator which predicts the channel parameters and the GPS receiver simulator which returns the position error. Its principle is illustrated in Fig. 1.

The input parameters of the multipath generator are the satellite position, the receiver position, and the 3D description of the environment composed of planar dielectric and metallic facets. The role of the multipath generator is to predict the channel parameters. These parameters become the input of the GPS receiver simulator [9] which returns the range estimation error between the satellite and the receiver due to multipath.

The multipath generator contains two main parts. The first one predicts the list of the electromagnetic fields associated with each multipath. These fields are computed by a method based on PO. The second one simulates the GPS receiver antenna. It allows the computation of the multipath parameters from the electromagnetic fields via the use of the effective vectorial height of the antenna.

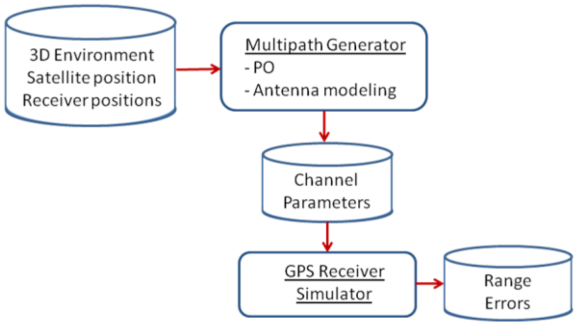

Fig. 1 Schematic structure of the deterministic simulator

Simulations can be performed either in static or dynamic configuration. In static configurations, the receiver and satellite are static. Hence, the inputs of the simulator are assumed time-invariant. A simulation is dynamic when either the receiver or the satellite are moving, which renders the input parameters time-variant.

The fields scattered by the facets are computed via an approach based on PO up to second order reflections. Once the scattered fields have been predicted in one point, the multipath parameters remain to be computed. These parameters are (a_k, τ_k, ϕ_k), the amplitude (or gain), arrival time and phase of the k-th path, respectively. In dynamic simulations, there is an additional parameter, the Doppler shift f_k^D of each multipath which also has to be computed. In such simulations the multipath parameters become $(a_k, \tau_k, \phi_k, f_k^D)$. These parameters describe entirely the multipath channel.

If $x(t)$ represents the waveform emitted by a satellite, the received signal $y(t)$ is a sum of attenuated, time-delayed versions of $x(t)$. Here we use the classical impulse response function for multipath channels, which leads to

$$y(t) = \sum_{k=1}^{K} a_k x(t - \tau_k) e^{j(2\pi f_k^D t + \phi_k)}. \qquad (1)$$

Once the multipath parameters are computed, the GPS range error prediction can start. The receiver simulator computes the estimated range between the receiver and the satellite. Hence, by knowing the real range, we deduce the multipath error.

2.2. Prediction based on Physical Optics

Within this approach, each illuminated surface generates reflected field. The simulator can compute the reflected field for metallic and dielectric multilayer facets and multiple reflections up to order 2. When the ground is planar and infinite, the ground reflections up to order 2 are computed by means of the image theorem. When the ground is not flat, it can be modeled with facets.

Besides, in [7]-[8] the use of PO has been justified and numerically validated.

3. HYBRID DETERMINISTIC-STATISTICAL PREDICTION

3.1. Nature of the Statistical Component

The general objective of the simulator is to map the characteristics of the GPS range error for a given environment. Hence, the prediction has to be site-specific, i.e. we have to consider the physical characteristics of the scene such that the buildings geometry and materials.

This objective may be achieved via the deterministic model since we have validated its accuracy for our application [7]-[8]. Nevertheless we know that the accuracy of the deterministic model also depends on the uncertainties in the scene data. Even a realistic 3D description of a scene as vast as an airport may lack of precision. It may contain uncertainties on the building positions, sizes and materials. Moreover such data do not take into account the time variability of the scene, e.g. the presence of other mobiles. In this context, the essence of the statistical prediction takes its origins in the defective scene description and its time variability.

In order to reach the general objective we base the statistical simulator on the deterministic simulator via Monte Carlo (MC) simulations.

3.2. General Principle

For a given deterministic scene, the uncertainties in the configuration are taken into account via adding a statistical variability to the 3D scene. From these uncertainties we perform MC simulations to derive the statistical moments of the GPS range error.

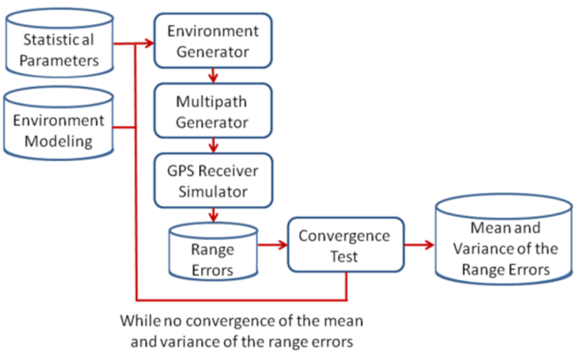

Fig. 2 Schematic structure of the hybrid simulator

The scene description and its statistical variability are the inputs of the simulator. At each iteration, the environment generator creates a new 3D scene from these inputs. Once the range error is computed, it is stored and analyzed in the convergence test module. While the convergence of the Monte-Carlo simulation is not reached, a new 3D scene is generated and a new range error is computed.

3.3. Scene Generation

The scene generation at each iteration is the basis of the statistical model. We assume that a complete 3D description of the scene is provided, which contains polygonal facets with material properties, and thicknesses. The issue is to determine which parameters in the scene description become random variables, and to associate with each of them a relevant probability distribution.

We have identified six parameters that we consider as statistical in the Monte Carlo simulation: the building positions in the horizontal plane, their orientations in the horizontal plane, their heights, their materials, the materials thicknesses, and the ground materials. These parameters are independently generated for each building, in order to insure the non-correlation of the complete geometry.

Regarding the material thicknesses, the building positions, orientations and heights, we chose to use normal distributions since it is a common way to model quantities that are expected to be around a particular value. The means are given by the positions, orientation angles and heights contained in the deterministic 3D scene. The standard deviations of these distributions are derived from the accuracy of the scene data which is assumed to be an input parameter of the simulator.

For illustration purpose we consider in Fig. 3 an ENAC campus building which position and size are assumed as known, it is the deterministic scene. The building is made of concrete walls with glass windows.

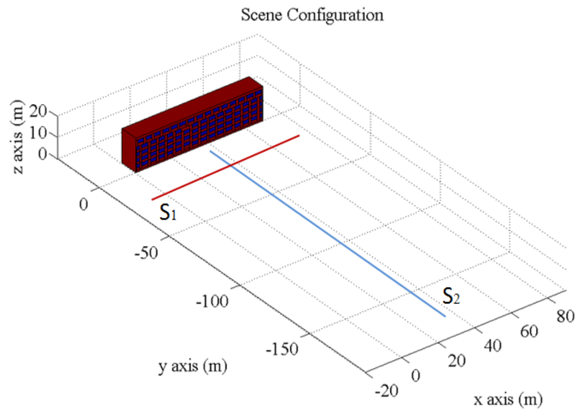

Fig. 3 Configuration of the ENAC campus building

In Fig. 4 we expose four scenes generated from the initial configuration by means of the environment generator. For illustration purposes the statistical variations are willingly overestimated. The standard deviations of the building position and orientation in the horizontal plane have been set to 10m and 10°. The standard deviation of the building height in percents has been set to 20%.

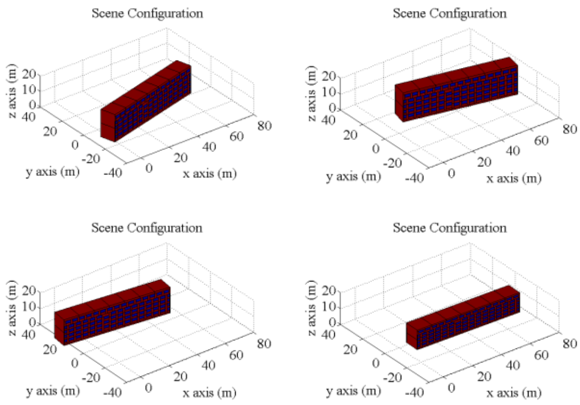

Fig. 4 Four scenes randomly generated from the ENAC campus building

Concerning the dielectric coefficients of each building materials they are chosen with an equal probability among a list of realistic coefficients. Indeed, since it is difficult for a given material to know its exact characteristics e.g. concrete or reinforced concrete, the dielectric parameters of each material follow a discrete uniform distribution.

4. TEST-CASE SIMULATIONS

4.1 Limits of the Deterministic Prediction

In order to confirm the necessity of the complementary statistical component we perform two deterministic simulations on the ENAC building. In the first case the building is at its initial position. In the second case its center is slightly modified of +5cm along the y-axis.

We compute the GPS range error along the segment S_1 as depicted in Fig. 3. This segment is at a distance of 30m from the façade, and its height is set to 8m in order to represent the average height of a GPS antenna onboard an airplane. The satellite elevation is 10°.

Concerning the receiver we consider the GPS signal L1 C/A. The antenna is modeled as isotropic, right-hand circularly polarized (RHCP) and with a polarization mismatch factor of –5dB. The DLL bandwidth is set to 1Hz, the PLL bandwidth is set to 10Hz, the integration time is set to 20ms and the early-minus-late chip-spacing is set to $0.5T_C$.

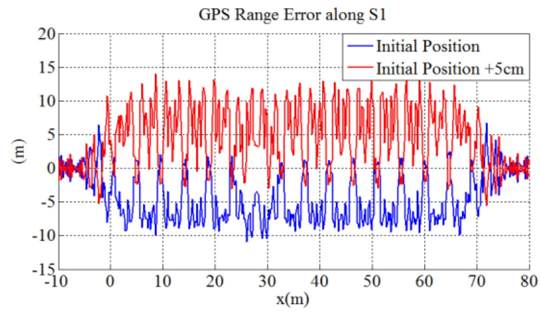

Fig. 5 GPS L1 C/A range error along the segment S_1

In Fig. 5 we observe important differences. This is explained by the wavelength of the GPS L1 C/A signal, which value is 19.03cm. Hence, moving the building center of few centimeters modifies greatly the multipath phase. As explained in [10], the GPS range error due to multipath is highly sensitive to the relative phase variation of multipath in comparison to the relative delay and amplitude variations.

Finally these results show that the range error is greatly impacted by an uncertainty of only few centimeters in the 3D scene. Hence they confirm the limits of the deterministic model and the interest of the statistical component.

4.2 Statistical Prediction

We consider the ENAC building with a standard deviation of 10cm of its position. In Fig. 6 and Fig. 7 we represent the statistical moments of the range error up to order two along the segments S_1 and S_2 (Fig. 3).

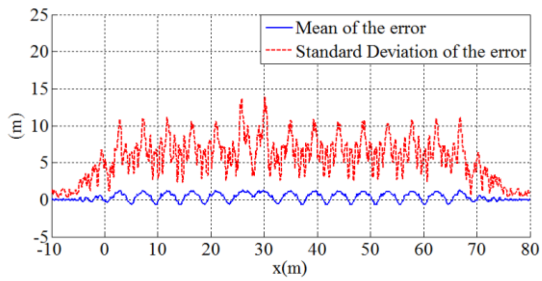

Fig. 6 Mean and standard deviation of the error along segment S_1

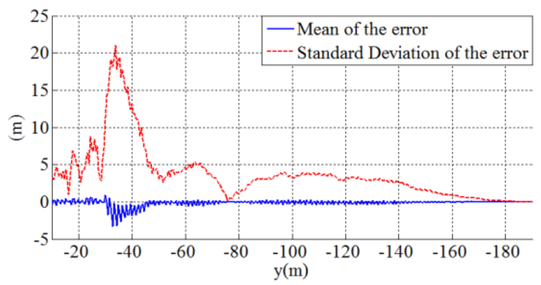

Fig. 7 Mean and standard deviation of the error along segment S_2

As expected the most significant range errors correspond to the specular reflection zone. Besides, we notice that the standard deviation values are much more important than the mean values. In this simulation, the standard deviation appears as a pertinent result to characterize the range error.

5. CONCLUSION

In this paper we have proposed a hybrid deterministic-statistical GPS multipath simulator adapted to airport navigation. This tool can be used to map the characteristics of the GPS range error for a given environment.

The need for the statistical prediction takes its origins in the defective scene description and its time variability. The hybrid simulator is based on the deterministic simulator via Monte Carlo simulations. Thus, it comprises the uncertainties of the scene.

Simulations on a test-case have confirmed the limits of pure deterministic predictions. Indeed, uncertainties of few centimeters in the scene lead to a poor estimation of the range error.

The results of the hybrid model have been analyzed on a test-case. It appears that a pertinent parameter to characterize the effect of multipath on GNSS systems may be the standard deviation of the range error. For future work, a study could be performed to confirm this statement.

6. ACKNOWLEDGEMENT

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