Development of a complete GPS simulator as a tool for siting of GPS reference stations on airport grounds

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DEVELOPMENT OF A COMPLETE GPS SIMULATOR AS A TOOL FOR SITING GPS REFERENCE STATIONS ON AIRPORT GROUNDS

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ABSTRACT

The siting of a GPS reference station on an airport is achieved by minimizing the influence of the environment on the pseudorange measurements, while complying with the operational installation constraints. The CNS Research Laboratory (URE-CNS) of the ENAC has started a study that aims at providing siting guidelines for the French Civil Aviation Authority. The first step of this study consists in implementing a GPS end-to-end simulator that will be used to establish the basic rules for the choice of the best location of the station on an airport with regards to multipath effects. Therefore, the initial goal of the simulator is to analyze the measurement errors induced by simple obstacles (ground, buildings, aircraft ...). The aim of this paper is to present the simulation software which is being developed and the initial results that were obtained.

I. INTRODUCTION

The multipath errors affecting the pseudorange corrections transmitted by the reference station can be reduced in several ways, including careful siting, good antenna design, and adequate signal processing. The study reported in this paper is focused on the selection of the siting location of the receiving antennas of an LADGPS reference station.

The perturbations caused by a complex airport environment on the pseudorange corrections transmitted by a Local Area DGPS reference station are difficult to determine because the transmitting satellites are in constant movement and because small obstacles can generate significantly disturbing signals. Therefore, it is necessary to elaborate a powerful tool to help the civil aviation authorities to select the best locations to install the reference stations. The functional principle of the siting tool can either be based on signal disturbance measurements at preselected locations or on computed error predictions based on mathematical models. Although both tools have major drawbacks, they are complementary.

Indeed, while the actual measurements correspond to real life situations, the variety of the field observations is restrained by physical constraints, and the assessment of all the safety critical situations is not possible in practice. On the other hand, the conformance of the simulations to reality is limited by the adequacy of the mathematical models, but initial results can be obtained faster for a very high number of representative situations, involving typical simple objects.

Therefore, the complete siting tool is built in two steps: first, a simulator is implemented, then a measuring instrument is developed, and both components are used in parallel to achieve our goal.

Several papers were published to report the work carried out on environmental effects on GPS measurements. Some researchers have used the Uniform Theory of Diffraction to model GPS signal strength and phase shift generated by the obstacles [Gomez S. et al, 1995], [Lippincott et al., 1996], while others have used a parabolic equation technique [Walker R. et al, 1996]. Some studies, such as [Perez Fontan F. et al, 1998] were applied to civil aviation, and others focused on airport operation [Braasch M., 1992], [Weiser M., 1998].

Our work intends to combine propagation simulation and receiver simulation to provide straight predictions of measurement errors. The software treats multipath as a perturbation of the whole transfer function of the propagation channel. The signal is not modeled as a discrete sum of delayed and attenuated replicas, but as a transmitted signal modified by the transfer function of a global propagation channel. Therefore, our program takes into account most of the effects degrading the pseudorange measurements.

The aim of this paper is to describe the simulation software which is being developed by the URE-CNS of the ENAC for the prediction of the errors induced by obstacles on the code and phase measurement made by a LADGPS reference station, and to present the initial results obtained from its execution. This software uses the successive positions of the GPS satellites to compute the disturbed signal received by the antenna of the station, which is in turn fed to a computer model of the receiver that delivers the measurement errors. The signal reaching the antenna is computed using a kernel developed by the ENAC for classical navaids called MUSICA [Roturier B., 1996]. This part of the software is based on the Uniform Theory of Diffraction (UTD).

In this paper, we first describe the key points of the software architecture such as the computing techniques and the software design. Following this, we present the essential channel characteristics that we have used to design the software, then we recall the principles of the UTD and explain how we applied this technique to GPS signals in airport environments. Next, the receiver model is presented, then the initial results provided by the software are shown. Finally, a conclusion is drawn from this study.

II. SOFTWARE ARCHITECTURE

We defined the structure of the program so that the time required to obtain the desired simulation results is reduced. Therefore, the simulator comprises three cascaded modules that communicate data to each other through the hard drive.

The first module reads an almanac file and computes the position of each satellite referenced in the almanac in the WGS-84 reference frame, for a given set of epochs. These positions are stored in a file on the hard drive of the computer for further processing. The second module reads the positions of the

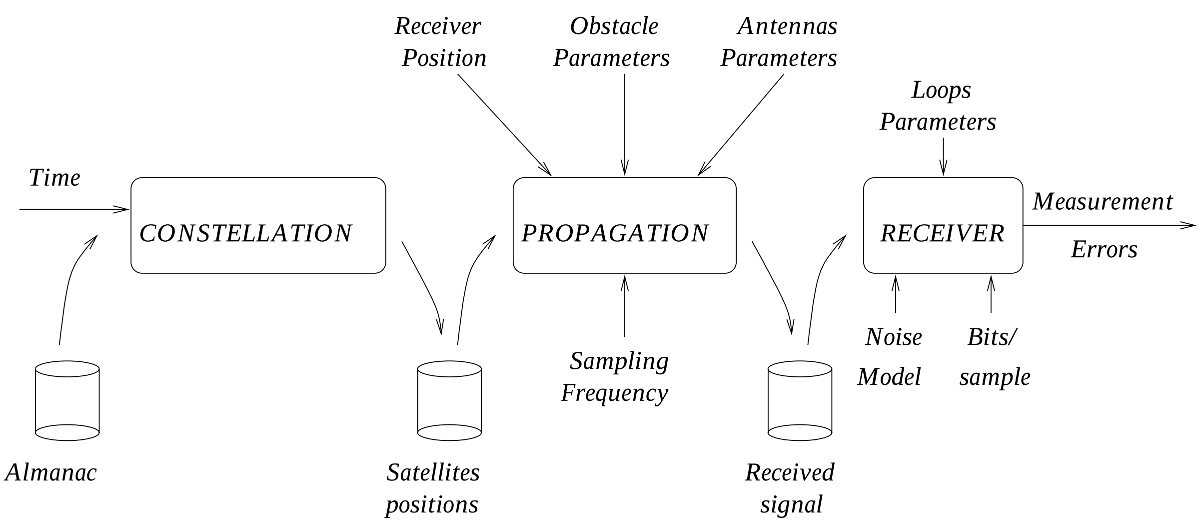

Figure 1: *Data flow for the simulator.*

satellites from the file, and computes the signal delivered by the antenna of the reference station to its receiver front-end module, taking into account the effect of all the surrounding obstacles. The computed signal is stored in a file on the hard drive. The third module reads the signal samples and computes the code and phase pseudorange measurement errors made by the receiver. These measurement errors are stored in a file on the hard drive.

We also tried to make full use of the properties of the mathematical models employed in the software in order to minimize the execution time.

The main simplification was derived from the properties of the propagation channel. As shown in the next section, its characteristics are constant during an interval which is larger than the time of stabilization of the tracking loops. Therefore, we could determine the evolution of the steady-state tracking error induced by obstacles with a time step larger than the internal receiver sampling period.

In addition, we did not implement all the sequential digital operations performed by the receiver after the arrival of a new signal sample. Instead, PLL and DLL error equations are used, delivering the steady-state measurement errors using the input signal, as presented in [Van Dierendonck, 1992].

III. PROPAGATION CHANNEL CHARACTERISTICS

In order to elaborate the adequate scheme to simulate the effect of the ground obstacles on the range measurements, a model of the equivalent transfer function of the disturbed propagation channel is determined.

In the GPS case, as the transmitter is mobile, the transfer function between the transmitted and the received signal varies with time. Therefore, the propagation channel is modeled as a time-variant linear filter [Proakis J., 1995].

The impulse response of the propagation channel, denoted $h(\tau; t)$, represents the response of the channel due to an impulse applied at time $t-\tau$ and received at time t. Denoting $s(t)$ the signal transmitted at time t, the received signal $r(t)$ can be expressed as the result of the filtering of s:

$$r(t) = \int_{-\infty}^{+\infty} s(t-\tau) h(\tau; t) d\tau \tag{1}$$

The propagation channel is modeled using its Fourier transform in τ, denoted $H(f; t)$. This model can be interpreted as the frequency effect of the channel on the transmitted signal, for a given position of the satellite at time t.

The transfer function is characterized through its variations in t and τ [Proakis J., 1995]. In our case, the transfer function of the channel is a deterministic process as it represents a finite number of replicas with computable features. However, the transfer function of such a channel is generally modeled as a stochastic process. These properties can be generalized to our deterministic case.

The rapidity of variation of the channel as a function of τ is characterized by the variations of the multipath intensity profile $h(\tau; t)$, for a fixed value of t. The radius of correlation T_m of $h(\tau; t)$ as a function of τ is called the multipath spread of the channel.

We can analyze the frequency variations of $H(f; t)$, Fourier transform of $h(\tau; t)$ in τ. The bandwidth of the spectrum $H(f; t)$ is the frequency domain equivalent of T_m. This parameter is denoted $\Delta f_c = \frac{1}{T_m}$ and is called the coherence bandwidth of the channel.

The rate of variation of the channel as a fonction of time shift t is characterized by the variations of $h(\tau; t)$ as a function of t for a fixed value of τ. The radius of correlation Δt_c of $h(\tau; t)$ is called the time of coherence of the channel.

The time of coherence of the channel Δt_c is at least of a few seconds [Renard A., 1998]. Therefore, we can assume that the time of coherence of the channel is larger than the time required by the tracking loops to reach their steady-state value. This property is used to simplify the simulation process: the characteristics of the channel are assumed to be constant during the time of stabilization of the tracking loops.

IV. UTD AS APPLIED TO GPS

The purpose of the propagation module is to compute the theoretical value of the electromagnetic fields sensed by the antenna. To this end, a deterministic technique is used to compute the value of the fields, based on the Uniform Theory of Diffraction (UTD). This method was developed at the ENAC in the framework of the elaboration of the MUSICA software (MUltipath SImulation for Civil Aviation) to study the effect of multipath on the signals radiated by the classical radionavigation aids such as ILS or VOR.

The computation of the electric field component is based on the ray theory. The electromagnetic ray is the portion of space that contributes significantly to the transport of the electromagnetic energy. This volume can be assimilated to the first Fresnel zone.

The rays that reach the receiver can have followed a complex path, resulting from several successive interactions with obstacles. However, only the rays that carry a significant energy to the receiver are considered.

The interaction between the electromagnetic wave and an object is computed in two steps: first the rays are traced, then the reflexion and diffraction coefficients are computed.

Ray tracing is performed according to the Fermat principle which states that rays follow the shortest path. Therefore, the rays correspond to the local minima of the time of propagation.

The program searches for all the stationary paths with an order of interaction lower or equal to 2 if the objects are isolated in space, or 4 for the objects placed on an infinite plane through the use of the imaging technique.

The transfer function $H(f;t)$ is computed through the evaluation of the amplitude and the phase of the electric field carried by each pertinent ray from the transmitter for a set of plane waves with frequencies distributed in the GPS bandwidth.

Using the transfer function $H(f;t)$ determined by MUSICA-UTD for a particular satellite, the propagation module computes the spectrum of the baseband signal r received by the antenna. This is done using the equivalent of (1) in the frequency domain at time t.

The simulations are decomposed in intervals with a duration lower than the time of coherence of the channel. Therefore, this duration is such that we can assume that the characteristics of the channel do not change. Thus, we assume that the satellite has a fixed position during the interval.

V. GPS RECEIVER SIMULATION

The last step of the evaluation is to use the disturbed input signal to determine the effect of the ground obstacles on the pseudorange measurements delivered by the reference station receiver. This is done through the simulation of the internal operations performed by the receiver. However, an accurate implementation of these operations would reproduce the performance of one particular receiver among hundreds of other realizations. Therefore, we chose to implement a generic receiver with a high number of configurable parameters.

Most of the operations performed inside a receiver are simulated. The signal delivered by the propagation simulation module is perturbed by additive noise with a user-defined level. Next, the effect of the front end filters is reproduced using typical digital filters models with variable parameters. Then, the sampled signal can be quantized with a configurable number of bits. Finally, a model of the code and phase tracking loops is applied.

Due to the long time required to implement and run a sequential model of a receiver, and the lack of adequacy of the equivalent linear models of the tracking loops for this study, it was decided to determine the tracking errors using error equations of the loops control signals. Indeed, this technique allows for a fast determination of the final steady-state errors of the tracking loops without considering their transition states.

For a given satellite position at time t, the steady-state estimates$\hat{\theta}_0$ and $\hat{\tau}_0$ are such that the signals controlling the DCOs of the tracking loops reach a stable zero lock point:

$$\begin{cases} V_{PLL}(t) = 0 \\ V_{DLL}(t) = 0 \end{cases} \tag{2}$$

These control signals depend on the incoming signal and the locally generated carriers and codes. Therefore, the receiver simulator searches for the code and carrier phase shift estimates that yield stable zero-crossings of the DCO control signals.

A few precautions have to be taken when computing the final tracking using this technique:

- The tracking error due to noise can not be observed directly, instead its level has to be determined using classical equations

- The signal to noise ratio has to be monitored to detect the situations where the loops lose track of the signal
- When the error signals show several zero-crossing values, like for example when the direct and the reflected signal are separated by a time delay greater than the Early-Late gate delay, the simulated result may not correspond to reality as the loops may lock on the reflected signal
- The error equations have to be adapted to be able to model complex DLLs that use a linear combination of several correlation values

VI. INITIAL RESULTS

The simulator was initially tested in a well-known obstacle setup involving a ground plate. The goal of this stage is to evaluate the conformance of the simulated values to theoretical predictions.

Although the propagation module is able to compute the signal from all the visible satellites, the initial results presented here were obtained using one single satellite signal.

In addition, as the receiver simulation module is not properly validated at the time this paper is written, only the waveforms reaching the tracking loops are analyzed and the error estimates are not reproduced.

The setup comprises an orbiting satellite, a ground plate, and a receiver located several meters above the ground plate. The nature of the soil was changed from metal to wet and dry soil. In each case, the transfer function was analyzed for a satellite located 5 deg and 75 deg above the horizon. The height of the receiving antenna was set to 3 m and 50 m. The predicted values showed good agreement with the observed values.

The next results show the waveform obtained when the ground is modeled as a metallic plate or wet soil 50 meters underneath the receiving antenna.

With the metallic plate, the transfer function exhibits extreme fading situations.

The received signal for that situation is plotted in figure 2. This situation generates a periodic loss of lock of both loops and can be detected from the observed power level of the signal.

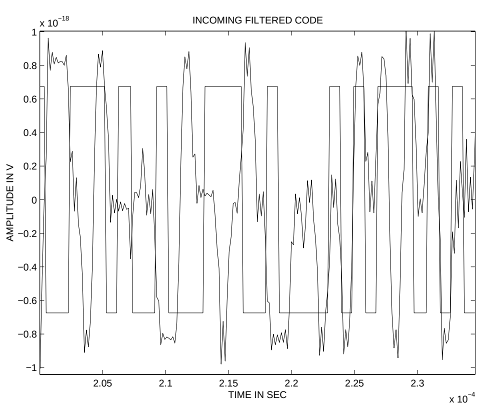

Figure 2: *Comparison between the received and the transmitted waveform when the only obstacle is a reflecting metallic plate for a receiving antenna placed 50 m above the plate.*

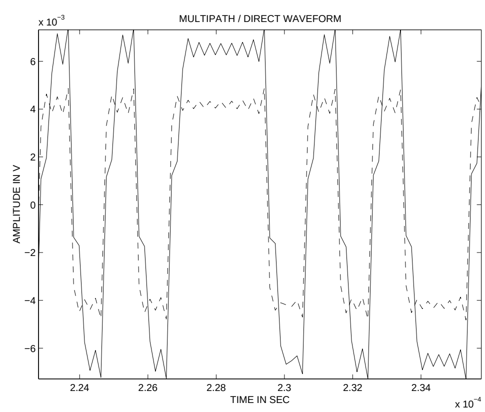

Figure 3: *Comparison between the received waveform with multipath (solid) and the received waveform without multipath (dashed). The only obstacle is a reflecting wet soil for a receiving antenna placed 50 m above the plate.*

In a more realistic case, the ground plate was modeled as wet soil. The reflexion coefficient takes on a complex value, and the received waveforms are compared in figure 3.

As we can see, the transitions of the signal affected by multipath are disturbed and the DLL will strike a compromise between the direct and the reflected code transitions.

VII. CONCLUSION

The CNS Research Laboratory is developing a tool to help the French Civil Aviation Authorities select the best locations to install LADGPS reference stations on airport platforms.

The first element of this tool is a simulator that can predict the measurement errors induced by typical generic obstacles.

This simulator is a software that combines a satellite constellation simulator, a propagation channel simulator and a receiver simulator.

The multipath generated by the obstacles are modeled by their effect on the transfer function of the channel using the Uniform Theory of Diffraction. Samples of the transfer function around the L1 frequency are taken with a time step larger than the internal receiver sampling period to improve the execution time.

The receiver simulator delivers the steady-state measurement errors of the carrier and code tracking loops for a set of typical receiver implementations.

The initial results obtained show good agreement with the theoretical predictions.

On-going development aims at increasing the number of test cases of the simulator and verifying the predicted values from field measurements.

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