

Development of an End-to-End GPS Simulator as a Tool for Siting GPS Reference Stations on Airport Platforms

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BIOGRAPHY

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Alain Renard is a GPS expert in the Advanced Studies division of the Navigation Department of SEXTANT AVIONIQUE. After graduating in 1972 as an engineer from the Ecole Nationale Supérieure d'Electronique et de Radioélectrique de Grenoble, he worked on radionavigation systems for commercial aircraft from 1973 to 1978. Then, he developed radionavigation systems based on OMEGA until 1988. Since 1988, he has been designing GPS and GLONASS navigation systems.

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. The simulator is comprised of three cascaded modules. The first module computes the satellite positions at every input epoch. The second module simulates the propagation channel. It is derived from the MUSICA tool (Multipath Simulation for Civil Aviation) that was previously developed by the ENAC for classical nav aids multipath simulation. It generates the disturbed GPS signal delivered by the antenna of the station to its receiver front-end. Then, this signal is handed to the last module, that simulates a generic GPS receiver and delivers the range measurement errors induced by the perturbations introduced in the propagation channel. The initial results show the effect of simple reflecting objects, such as the ground and metallic surfaces.

I. INTRODUCTION

The pseudorange measurements made by a GPS receiver are disturbed by a sum of different errors such as satellite clock bias and SA, atmospheric propagation errors, tracking loop noise, and errors induced by the multipath propagation of the signal. The amplitude and phase of the reflected and diffracted signals reaching the antenna depend on a high number of factors. Among them are the nature and size of the diffracting obstacles, the relative location and orientation of the receiving antenna with respect to these obstacles, the pattern and polarization of the antenna, and the processing operations

performed within the receiver. Therefore, the multipath-induced errors affecting the measurements made by two distant receivers are different. As a consequence, the pseudorange corrections broadcast by a Local Area DGPS reference station can contaminate the measurements made by the user receiver with multipath errors that are proper to the reference station.

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.

As a general rule, the presence of obstacles around any radionavigation aid on an airport ground must comply with the requirements stated in [ICAO, 1996]. Moreover, [ICAO, 1983] defines Obstacle Clearance Surfaces that specify the maximum height of obstacles for the safe operation of aircraft on the airport. Furthermore, each operating country can define its own rules to reduce the threat of obstacles perturbing the radiated signals.

The current version of [ICAO, 1996] specifies the controlled traffic areas to be defined around the antennas for a safe operation of the classical navaids such as ILS, VOR and MLS. Two types of areas are defined. The critical area is a specific area on the ground surrounding the transmitting antenna where the presence of any vehicle is forbidden during the navaid operation. The sensitive area is an area surrounding the critical area where the presence of any vehicle is controlled in such a way that the signal degradation is acceptable.

In addition, the French CAA has established constraint areas called 'servitude' areas surrounding navaids transmitters and receivers where the edification of any possible obstacle is strictly controlled.

The location and size of the critical and sensitive areas, and of the servitude areas, for the safe and efficient operation of LADGPS reference stations have yet to be defined by ICAO. These areas and their traffic control rules will be such that the effect of obstacles will not degrade the service level under the minimum performance requirements for the LADGPS reference station [RTCA, 1998].

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 pre-

dictions 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

The approach chosen for the development of the software is a compromise that aims at reducing both the development and execution times, and maximizing the portability of the program.

As a consequence, we chose to develop the software in MATLAB. First of all, as the MUSICA UTD kernel is a MATLAB program, and as numerous utility packages are available for digital signal processing, we decided to write all the procedures in MATLAB. Development is easier than with an assembled programming language, and the program scripts can be run on any machine set up with the command interpreter and the proper toolboxes. But, as some routines are very slow, precisely because instructions are interpreted, we decided to produce compiled libraries from the slowest parts of the program.

Keeping up with our strategy, 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.

As shown in figure 1, 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.

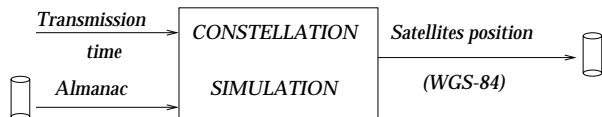


Figure 1: *Data flow for the constellation simulator.*

The second module reads the positions of the 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, as outlined in figure 2. The computed signal is stored in a file on the hard drive.

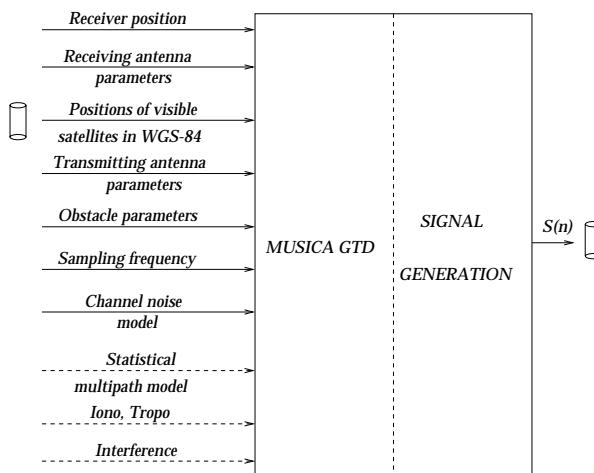


Figure 2: *Data flow for the propagation simulator.*

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. The data flow for this module is summarized in figure 3.

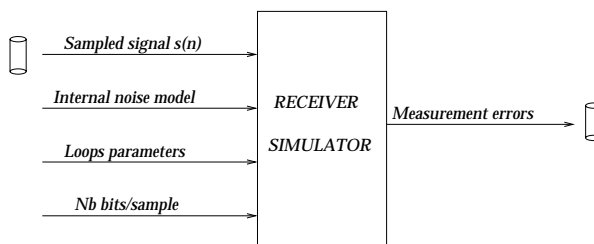


Figure 3: *Data flow for the receiver simulator.*

Each one of the three main modules is set up as an independent executable program that can be run from the MATLAB command window, communicating data with the other modules through the hard drive. Therefore, the propagation and the reception functions can be run separately with different values of their own configuration parameters without requiring their joint execution.

Finally, we 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

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 :

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

In the deterministic case, the signal can be modeled as a sum of discrete multipath components, so the channel can be represented as:

$$h(\tau; t) = \sum_{n=0}^{N(t)} \alpha_n(t)g_n(\tau - \tau_n(t)) \quad (2)$$

where

- N is the number of paths followed by the signal to reach the antenna. This number varies with time.
- g_n is the transfer function associated with path n . In general, the phase shift caused by g_n on the transmitted signal does not depend linearly on frequency: g_n is representative of a dispersive medium.
- α_n is the attenuation affecting replica n .
- τ_n is the delay associated with path n

The model presented in (2) is not ideally suited for our receiver simulation as the number of valid paths varies with time and requires a dynamic algorithm working on N , α_n and τ_n . Instead, 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 .

Figure 4 shows an example of the variation of the propagation channel in the GPS frequency band as computed with our simulator.

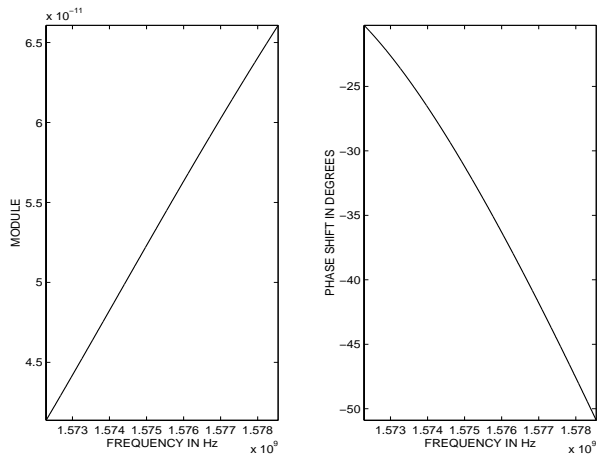


Figure 4: Example of variation of the module and phase of the propagation channel around the L1 frequency. The transfer function was obtained from the simulation of a signal reflected by wet soil.

Figure 5 shows the evolution of the group delay of the propagation channel over frequency as computed using our simulator. As we can see, the medium does appear to be dispersive in the GPS bandwidth, as the group delay varies over frequency by almost 5 meters. This is in line with the model presented in (2).

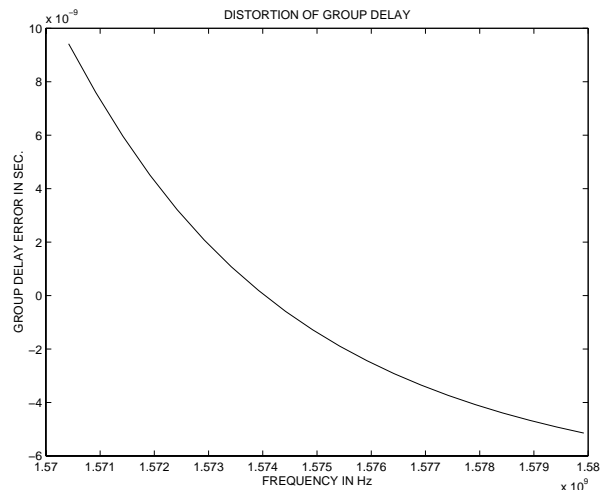


Figure 5: Example of variation of the group delay of the propagation channel around the nominal group delay when the signal is reflected by the Earth's surface. The group delay varies almost by 5 meters in the GPS C/A band.

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.

Figure 6 shows an example of $H(f; t)$. As we can see, the coherence bandwidth Δf_c is about as large as the GPS bandwidth.

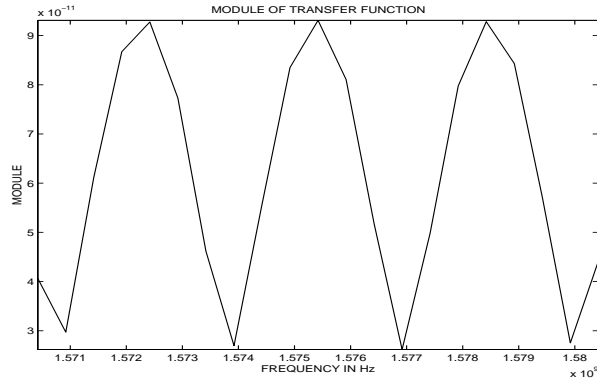


Figure 6: Example of variation of the transfer function of the GPS propagation channel ± 10 MHz around L1. This function was obtained from the simulation of a signal reflected by wet soil for a receiving antenna located 50 m above the ground.

The rate of variation of the channel as a function 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 variations of the Fourier transform of $h(\tau; t)$ in t , denoted $H(\tau; \lambda)$ characterize the impacts of the movements of the mobile on the frequency components of the received signal. Its correlation radius $B_d = \frac{1}{\Delta t_c}$ is called the Doppler spread 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 method employed is an asymptotic technique that solves the Maxwell relations established in any point. The technique assumes that

- The simulated obstacles are in a small number, and the position, the nature and the shape of the objects are well defined.
- The surface of the obstacles is smooth, although slightly rough surfaces can be modeled as smooth surfaces with a lower reflexion coefficient.
- The size of the objects is large compared to the wavelength of the considered signal.
- The phase center, polarization and radiation patterns of transmitting and receiving antennas are known.
- The dielectric parameters of all the propagation media, including the obstacles, are known.
- The geometry of the obstacles is defined by a set of polygons with a given shape and convex revolution ellipsoids.

Figure 7 shows an example of the application of the ray-tracing software to GPS with airport structures.

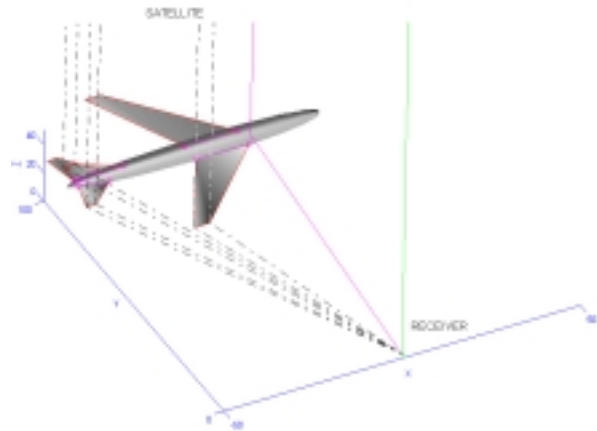


Figure 7: Example of ray-tracing involving reflection and diffraction off a B-747.

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.

There are 5 types of rays, sorted by decreasing power:

- the direct ray

- the reflected rays
- the knife-edge diffracted rays
- the point diffracted rays
- the creeping rays

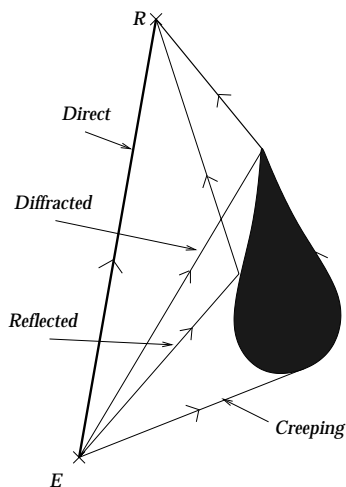


Figure 8: Illustration of the different considered rays.

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.

The baseband equivalent signal entering the tracking loops is

$$c_f(t) = (f * c)(t) \quad (3)$$

where

- f is the complete baseband equivalent filter representing the effect of the propagation channel h and the action of the front-end filters g : $f = h * g$.
- c is the transmitted code

Figure 9 shows an example of the deformations affecting the signal entering the tracking loops.

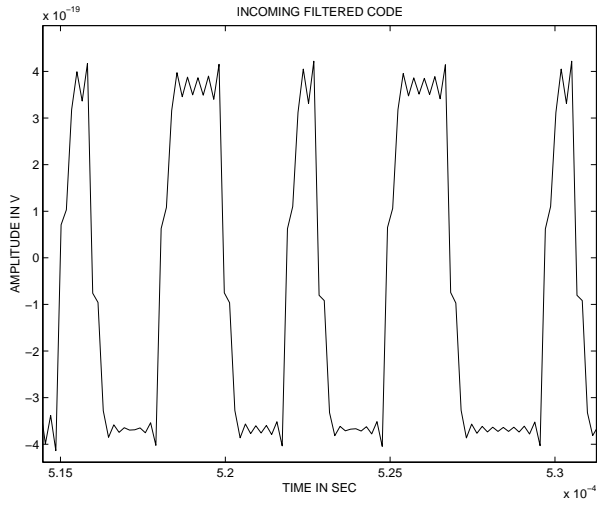


Figure 9: Example of baseband received waveform.

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:

$$\begin{cases} V_{PLL}(t) = 0 \\ V_{DLL}(t) = 0 \end{cases} \quad (4)$$

These control signals depend on the incoming signal c_f 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.

Analytical expressions of these signals can be given using classical expressions based on model (2): c_f can be written as

$$c_f(t) = \sum_{n=0}^{N(t)} \alpha_n(t) c_{f_n}(t - \tau_n(t)) \sin(2\pi f_0 t - \theta_n(t)) \quad (5)$$

where $\theta_n(t)$ is the phase shift experienced by the carrier on each path n .

The error signal controlling the DCO of the Costas loop can be written as the product of the I and Q channels [Doris D., 1997]:

$$V_{PLL}(t) = V_I(t) \times V_Q(t) \quad (6)$$

where

- $V_I(t) = \frac{1}{2} \sum_{n=0}^{N(t)} \alpha_n(t) R_{f_n}(\hat{\tau}_0 - \tau_n(t)) \sin(\hat{\theta}_0 - \theta_n(t))$
- $V_Q(t) = \frac{1}{2} \sum_{n=0}^{N(t)} \alpha_n(t) R_{f_n}(\hat{\tau}_0 - \tau_n(t)) \cos(\hat{\theta}_0 - \theta_n(t))$
- $\hat{\tau}_0$ is the PLL estimate of the carrier phase.
- $\hat{\theta}_0$ is the PLL estimate of the carrier phase.

- R_f is the intercorrelation between the punctual code and the incoming code

In the absence of velocity aiding, the error signal controlling the DCO of a classical Early-Late coherent DLL is

$$V_{DLL}(t) = \sum_{n=0}^{N(t)} \alpha_n(t) e^{i(\hat{\theta}_0 - \theta_n(t))} \left[R_{f_n}(\hat{\tau}_0 - \tau_n(t) + \frac{\Delta}{2}) - R_{f_n}(\hat{\tau}_0 - \tau_n(t) - \frac{\Delta}{2}) \right] \quad (7)$$

In the same case, the error signal controlling the DCO of a classical non coherent DLL is

$$V_{DLL}(t) = \left| \sum_{n=0}^{N(t)} \alpha_n(t) e^{i\theta_n(t)} R_{f_n}(\hat{\tau}_0 - \tau_n(t) + \frac{\Delta}{2}) \right|^2 - \left| \sum_{n=0}^{N(t)} \alpha_n(t) e^{i\theta_n(t)} R_{f_n}(\hat{\tau}_0 - \tau_n(t) - \frac{\Delta}{2}) \right|^2 \quad (8)$$

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, as the reflexion coefficient of metal is constant and equal to 1, equation (2) can be written as:

$$h(\tau; t) = \alpha(t)\delta(\tau - \tau_0(t)) + \alpha(t)\delta(\tau - \tau_1(t)) \quad (9)$$

The Fourier transform of (9) in τ is:

$$H(f; t) = \alpha(t)e^{-i2\pi f\tau_0} + \alpha(t)e^{-i2\pi f\tau_1} \quad (10)$$

The transfer function exhibits extreme fading situations as predicted from (10):

$$|H(f; t)|^2 = \alpha(t)^2 (2 + 2\cos(2\pi f(\tau_1 - \tau_0))) \quad (11)$$

The received signal for that situation is plotted in figure 10.

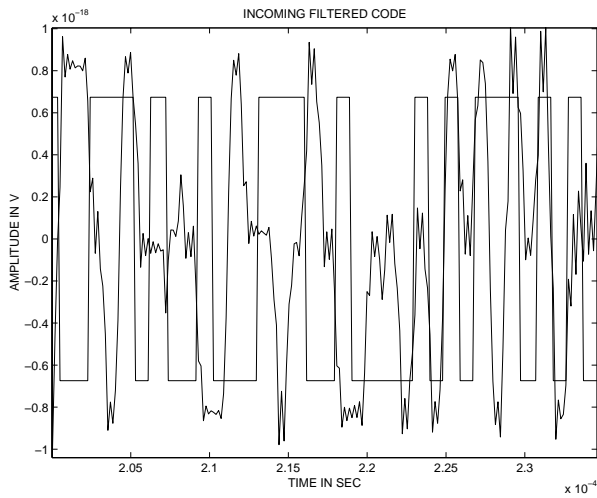


Figure 10: Comparison between the received and the transmitted waveform when the only obstacle is a reflecting metallic plate for a receiving antenna placed 50 m above the plate.

This situation generates a periodic loss of lock of both loops and can be detected from the observed power level of the signal.

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 11.

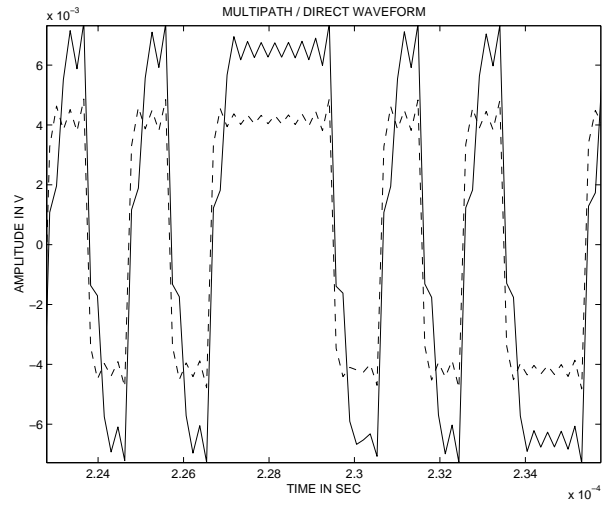


Figure 11: Comparison between the received waveform with multipath (solid) and the received waveform without multipath (dashed). The only obstacle is a reflecting wet soil for a receiving antenna placed 50 m above the plate.

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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