Evaluation of a GNSS receiver performance in different multipath environments with a novel real-time multipath simulation system

Tommaso Panicciari, *Spirent Communications (Tommaso.Panicciari@spirent.com)*
Mohamed Ali Soliman, *Spirent Communications (Ali.Soliman@spirent.com)*
Grégory Moura, *OKTAL Synthetic Environment (GMoura@oktal-se.fr)*

BIOGRAPHY (IES)

Tommaso Panicciari (Ph.D.) received a B.S. and M.S. in telecommunication engineer from Politecnico of Turin (Italy), where he also worked as research assistant on GNSS reflectometry. He obtained the Ph.D. in 2016 from the University of Bath (UK). His research focused on novel imaging techniques for the detection and localization of structures in the ionosphere. He also gained experience in data assimilation and GNSS software receivers. Since 2016 Tommaso Panicciari has been a software/project engineer at Spirent Communication where his main activity focuses on spoofing and multipath simulation.

Mohamed Ali Soliman. In his role as a Tailored Solutions Engineer, Ali is responsible for working with customers to define, develop and deliver innovative solutions that are not covered by Spirent's COTS product portfolio. Ali started his career in Spirent as a Placement Student Engineer then took a Graduate Hardware Engineer role for a year before moving to his current position. Ali has a BEng Honours degree in Electronic and Communications and currently doing Master's degree in Telecommunications with Business.

Grégory Moura graduated from the top French Institute of Aeronautics and Space (ISAE-SUPAERO) in 2004. He received a M.S. of Cosmology from Université de Toulouse III (France) in 2004. Since 2005, he has been working as a project manager and expert in the field of GNSS propagation simulation. He is currently managing the GNSS activities of the French company OKTAL Synthetic Environment. He is in charge of the management of the simulator SE-NAV that computes the propagation and the reception of GNSS signals in constrained environments.

ABSTRACT

Multipath can be one of the main sources of error in a GNSS receiver in urban environment. Multipath errors can vary from a few meters to hundreds of meters according to the geometry of the satellites and environmental conditions. The characterization and study of multipath is complex but important when its effect needs to be compensated in the position or navigation solution. The disruption caused in the received GNSS signal by the surrounding environment can be assessed in simulation. In fact, simulation is a powerful tool to test the performances of GNSS systems and services in controlled and repeatable conditions. Furthermore, simulations provide users with a method to characterize the multipath, to study and test advanced and new techniques for multipath rejection, to evaluate the reception in a given location and at a specific time (i.e. mission planning), and to simplify the analysis of specific events (i.e. for mission debriefing).

The aim of this paper is to analyze the performances of a GNSS receiver with an innovative real-time system that allows the reproduction of an authentic multipath environment. The system combines a state-of-the-art GNSS simulator and an advanced GNSS propagation model. The propagation model relies on a 3D-model reconstruction of the urban environment, which allows the generation of a multipath signature that strictly depends on the location of the receiver's antenna. This becomes important for a moving vehicle since it may be affected by very different multipath conditions depending on the trajectory and location. Then, the performances of a GNSS receiver are compared between simulated and field test data. The results show that it is possible to simulate realistically the multipath environment and to obtain performances that are comparable to a real case scenario.

INTRODUCTION

The position, navigation, and time accuracy can be degraded in the urban environment by the multipath phenomenon. The interference caused by multipath can increase the position error considerably if not compensated properly. In situations where the Line-Of-Sight (LOS) is obscured by surrounded buildings, the receiver may still be able to navigate by using the Non-Line-Of-Sight (NLOS) signal, which originates from single or multiple reflections/diffractions of the GNSS signal.
The use of 3D models has been one of the preferred solutions to recreate the multipath environment as seen by a GNSS device. This solution brings the potential to generate a multipath signature that is representative of the position of the antenna in a specific time. However, this solution comes with a certain degree of complexity. In fact, an accurate 3D model is required to simulate the obscuration of the GNSS signal, and a good propagation model is needed to generate phenomena like reflection and diffraction.

3D models have become more accurate and widely available and are mainly used to predict the satellite availability in specific locations, for example [1][2] used a 3D model to evaluate the signal availability in urban canyon. In [3] a propagation model was implemented for both reflection and diffraction. In the same paper, a final comparison of simulated with field data was performed but, still, the comparison mainly focused on the signal availability.

Other uses of 3D models are as an aiding tool to assist navigation sometime together with INS solution. For example, in [4] an Extended Kalman filter was augmented with a 3D model in order to make the navigation in a critical environment (e.g. with many NLOS signals) more robust. In another paper [5] the 3D model was used to remove the NLOS information from the raw data similarly to [6] where the NLOS was removed before the positioning calculation. In [7] the satellites that contributed with only NLOS where excluded from the navigation solution. The NLOS information was obtained by looking at absence of LOS in the 3D model at the given position.

In this paper a 3D urban model is used in a new real-time system capable to simulate multipath reliably and in different environments is presented. The system is capable to simulate multiple GNSS constellations and is comprised of a Spirent Simulator (and SimGEN®) and SE-NAV. SE-NAV is interfaced with SimGEN® (real time close loop) thanks to the SimREMOTE protocol: SimGEN® controls SE-NAV, sends the location of the emitters and the receiver and SE-NAV sends back the obscurations and multipath information. Initial performances of SE-NAV in terms of pseudorange erorrs were assessed in [8]. The authors in that paper illustrated some results based on the comparison between simulated and field test data showing that SE-NAV was capable to simulate realistically the GPS signal.

This article describes the SimGEN® + SE-NAV system and shows a comparison between simulated and field measurements. The comparison is based on signal availability, horizontal error, C/N_0, pseudorange and Doppler residuals.

RAY-TRACING WITH 3D MODELING

The simulator SE-NAV, developed by the company OKTAL Synthetic Environment, models the propagation of RF signals in constraint environments considering obscurations and multipath. SE-NAV uses a proprietary Ray Tracing kernel (based on Bounding Volume Hierarchy techniques using GPU resources) coupled with Geometrical Optics and Uniform Theory of Diffraction to compute the interaction between the signal and the local environment. SE-NAV uses Synthetic Environments (i.e. geometrical and physical modelling of a real or realistic environment) to compute the impact of the obscurations (mainly availability issues) and multipath (fading effects, performance problems).

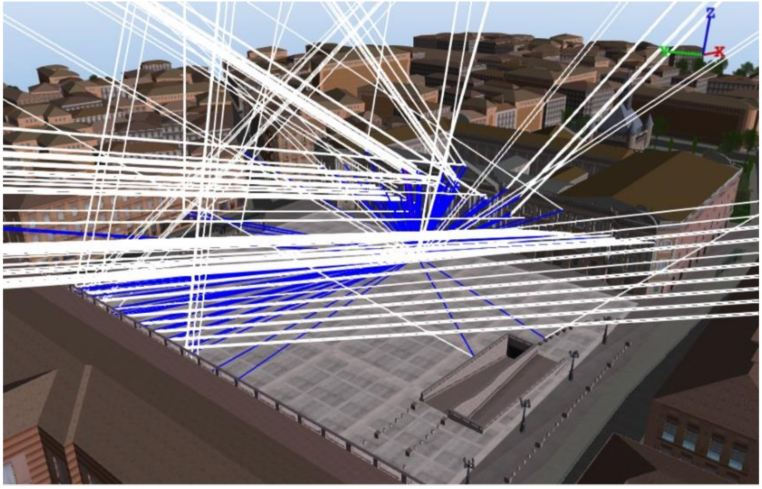

Figure 1. Example of SE-NAV simulation

The objective of ray-tracing is to find all the possible paths from the observer to the source of the signal considering a limited number of interactions per emitted rays. A ray-tracer (or ray-tracing algorithm) uses a primary grid to cast primary rays. Then, it iteratively computes the possible interactions between these rays and the virtual scene (often defined using triangles). If those interactions exist (i.e. if they are compliant with the law of Physics) and if the number of interactions to reach the emitter is below the maximum number of interactions set by the user, then a ray (or multipath) is created. This is a deterministic method that can be used to calculate the obscuration due to the local environment (and therefore detect the signal availability) and the geometrical characteristic of the computed path. Combined with a physical modelling, the path attributes such as received power, delay, Doppler, and phase can also be computed.

The main advantages of Ray Tracing techniques to model RF propagation are:

- It models most of the signal reaching the receiver for a virtual environment.
- As it is a deterministic method, the more realistic the environment modelling, the more compliant with reality the results.
- The specular multipath can be displayed in 3D and their attributes (e.g. receiver power, phase, polarization, Doppler, geometry of the ray) are known. It is relevant to study the contribution of some part of the environment on the propagation of the signal.

Nonetheless, Ray tracing techniques have three major drawbacks:

- They are time consuming algorithms. Indeed, depending on the complexity of the scene (basically the number of triangles), a combinatorial problem to find the possible multipaths reaching the receiver makes the ray-tracer very slow. That is the reason why the most difficult task to achieve during the coding of a ray-tracing algorithm is to develop acceleration techniques to quicken the computation process. Several solutions exist to either improve the intersection determination (for instance, based on spatial hierarchies such as Bounding Volume Hierarchies or BVH techniques), or to decrease the number of cast rays (often based on adaptive sampling techniques), or even to replace rays with beams or cones. Moreover, it is possible today to use the resources of graphic boards to accelerate the computation. Indeed, as ray-tracing can be coded by a large number of primary functions that can be treated simultaneously, it can be easily ported into GPU.
- Their accuracy depends on the resolution of the primary grid. Details and therefore rays may be missed if the 3D scene is made of small details. This issue is called aliasing. Aliasing artefacts are raised for instance in parts of the scene with abrupt changes (such as edges) or in complex areas with lots of constituent objects. Solutions (or antialiasing techniques) exist to overcome this issue such as adaptive or stochastic samplings.
- When it is combined with Geometrical Optics, these algorithms only compute the specular rays. Even if some techniques exist to model the scattering signals, only Physical Optics codes can render the global signal with high fidelity.

MULTIPATH SIMULATION SYSTEM

The system can model two of the main propagation issues encountered in urban environment, such as obscuration (which lead to limitations in signal availability) and multipath (which generates interference that causes fading of the signal and positioning errors). To model realistically such a complex phenomenon, the system uses a GPU raytracing algorithm combined with Geometrical Optics and Uniform Theory of Diffractions. The ray tracing algorithm relies on 3D-model reconstructions of the urban environment. The computed obscuration and multipath effects are then used to generate signal corrections (in terms of power, delay and Doppler variation) to be used in the Spirent GNSS simulator, which generates the carrier, code, and navigation messages for different GNSS constellations into a single RF output. Some of the advantages of this system is its ability to run in real time, and to visually show all the reflections/diffractions of the GNSS signals that cause multipath interference.

Figure 2 shows the diagram of the system set-up in conductive mode. The system includes a SE-NAV PC controller, SimGEN® controller, Spirent simulator, and DUT. A different mode is also available called Over The Air (OTA). This mode uses an anechoic chamber and a set of antennas distributed uniformly to generate the RF signal including the multipath. The DUT can then be placed at the center of the chamber and will be able to receive LOS and NLOS signals from different angles of arrival.

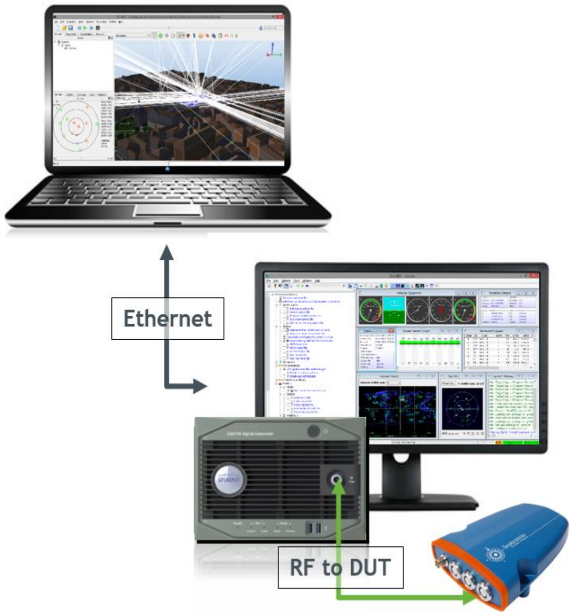

Figure 2. System diagram that shows SE-NAV controller (top), SimGEN® and Spirent simulator (bottom), and the device under test connected to the RF output of the simulator.

SimGEN® is used to generate and control the generation of the satellite signals (including multipath) at RF, whilst SE-NAV is used to calculate the propagation information (delay, doppler, and attenuation) of the reflected signals through a 3D urban model. SE-NAV is interfaced with SimGEN® by means of SimREMOTE commands. SimREMOTE is a package of Remote Control facilities that greatly enhances the flexibility of SimGEN®. Those commands can be sent and received through the TCP/UDP protocol with different data streaming rates (10 Hz was used for this paper).
It is also important to point out that SE-NAV computes all the possible multipath signal generated by the 3D model given the position of the satellites and receiver. However, the physical limitation of the number of channels in the simulator causes the rejection of some rays. This rejection or filtering process can be done according to power (used in this paper) or delay.

EXPERIMENT SET-UP

A set of different field test campaigns where carried out during the days of 9 August 2016. Each of those campaigns aimed to evaluate the ability of the system to assess the performances of a GNSS receiver using simulated signals in urban environment. Figure 3 shows the trajectory (blue line) used for the experiment in urban (San Jose) environment with a static (a) and dynamic (b) scenario.

Figure 3. A set of three measurement campaigns where carried out during the days 9 and 10 August 2016: a) urban environment with static antenna; b) urban environment with dynamic antenna.

Figure 4 shows a rough idea of the detail that was put into the 3D scene for San Jose. The buildings in close proximity of the antenna (green area in Figure 4b) contain details like material, 3D facade, and other details like windows. Instead, the buildings far from the antenna where only corrected for height and the material was modeled as concrete only.

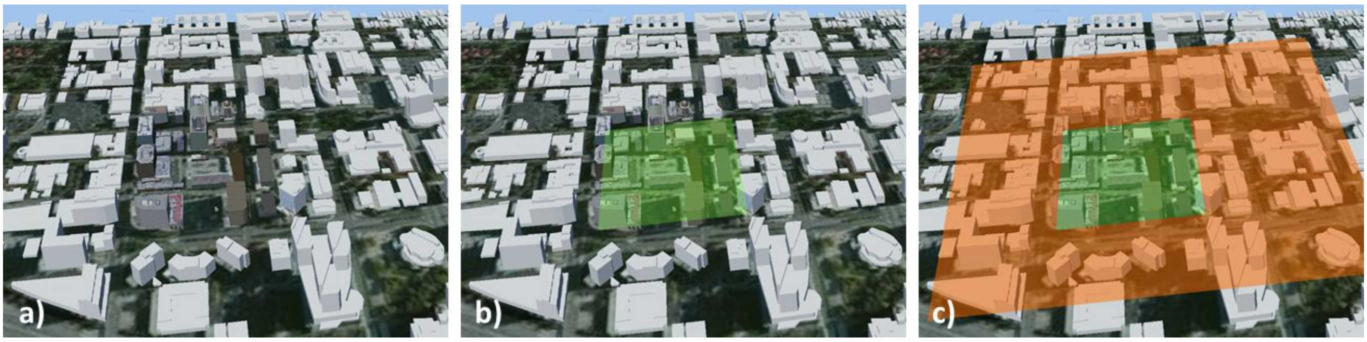

Figure 4. The San Jose model contained most of the details around the receiver antenna (b), whilst in only height correction for the building far from the antenna (c).

An exception was done for a building in San Jose since its complexity in the architecture was believed to contribute with more reflected rays than with a more simplistic box (concrete) model (Figure 5).

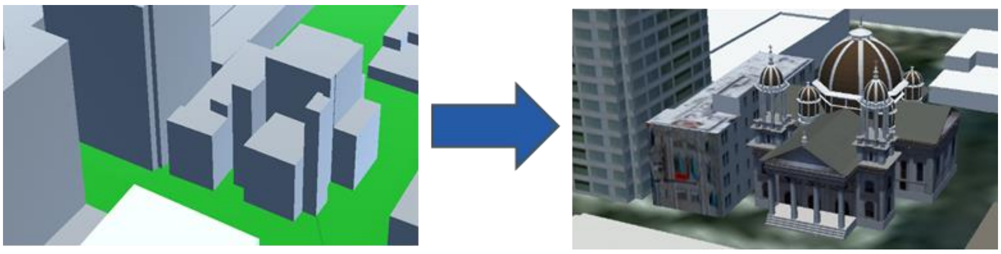

Figure 5. Improvement (right) in a San Jose building since its complexity in the architecture was believed to generate more reflections than the ones obtained with a more simplistic box model (left).

EXPERIMENT RESULTS

A direct comparison of carrier-to-noise (C/N_0) power, pseudorange residual, and Doppler residual was performed between the field test and simulation.

SAN JOSE STATIC - RESULTS

Figure 6 shows the results obtained from San Jose (static scenario) for satellite PRN02 (a-c) and PRN06 (d-f). The figure shows the carrier-to-noise (C/N_0) ratio (a, d), pseudorange residual (b, e), and Doppler residual (c, f) for field test (blue line) and simulation (red line). Although the simulation creates sometimes deeper fading than in the field test (a, d), a first comparison indicates a good correlation of simulated data with field test data. The signature of the multipath caused by this urban environment is visibly captured in the simulation. More interestingly, the pseudorange residuals (b, e) and, although to a lesser extent, Doppler residuals (c, f) also indicate that the model is replicating the dynamics of the multipath environment in close correlation with the field test.

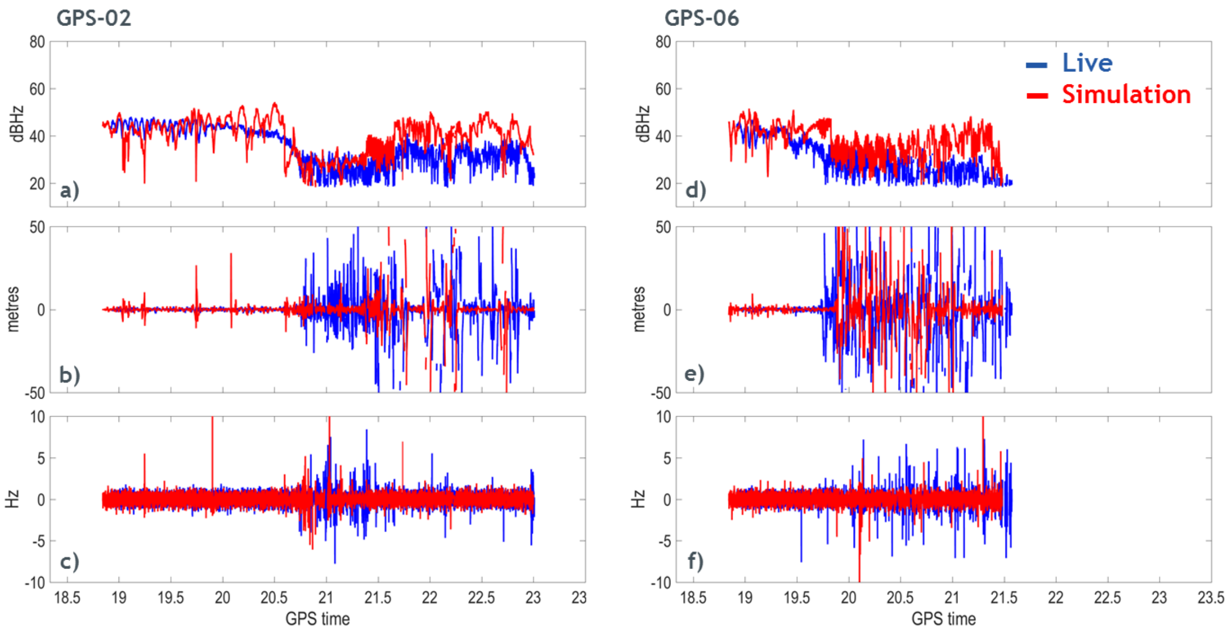

Figure 6. Carrier-to-Noise ratio (top), pseudorange residual (middle), and doppler residual (bottom) for PRN 02 (left column) and PRN 06 (right column).

The following picture shows the C/N_0 obtained from the field data (blue), and simulated data (red) with only obscuration (a) and with obscuration and multipath (b) for the static scenario. It can be noticed that the receiver can still track PRN02 without the Line-Of Sight (LOS), therefore, relying on just the Non-Line Of Sight (NLOS) signal. This can be clearly seen in Figure 7a where a sudden drop in power is associated to an obscuration of the same satellite (based on our 3D urban model). Figure 7b shows the C/N_0 obtained from the simulation (red line) when both obscuration and multipath were enabled. In this case the receiver could track the satellite even in the case of only NLOS as in the field-test.

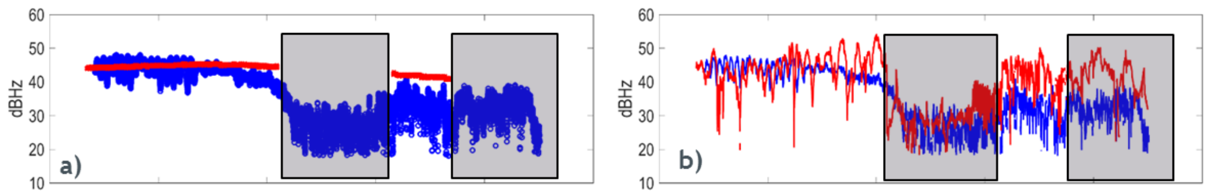

Figure 7.Carrier-to-Noise ratio for satellite PRN02 with only obscuration (a) and with multipath (b).

The positioning error for the San Jose static scenario is shows in Figure 7a. The simulation and field-test data have a comparable error. It can be noticed that the error is relatively big at the beginning of the simulation and decreases after time 20.6 (decimal hours). At the time 22.3 a moderate increase of the positioning error is visible in the field data until the end of the test. The simulation shows a similar trend also in this last part of the test but tends to generate a higher positioning error.

The satellite availability is shown in Figure 8b for both simulated (red) and field test (blue). The availability of the satellites generated with simulated data is in close relationship with the field data. However, some satellites could not be tracked in the simulation.

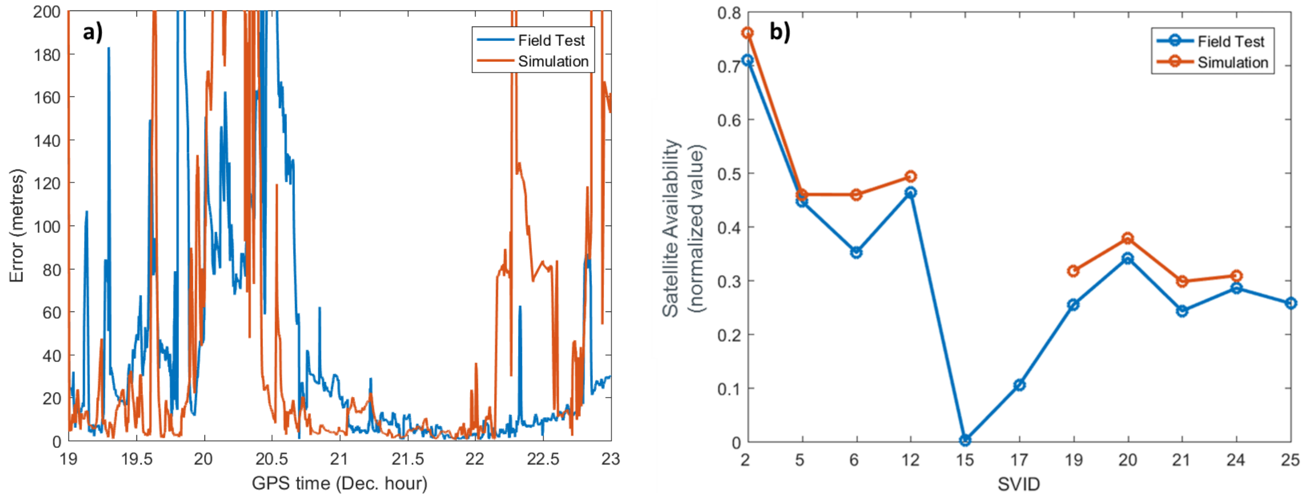

Figure 8. Positioning error for field-test (blue) and simulation (red); (b) Satellite availability for field data (blue) and simulation (red).

The importance of the accuracy of the 3D scene is evident in this example. In fact, it was noticed that one of the buildings that we simulated as a simple concrete box was more complex in the real environment. Therefore, we applied some modifications to scene as in Figure 9 and run the simulation again. A general improvement in the results was visible but most important was that the missing satellites could be finally tracked by the receiver (Figure 10).

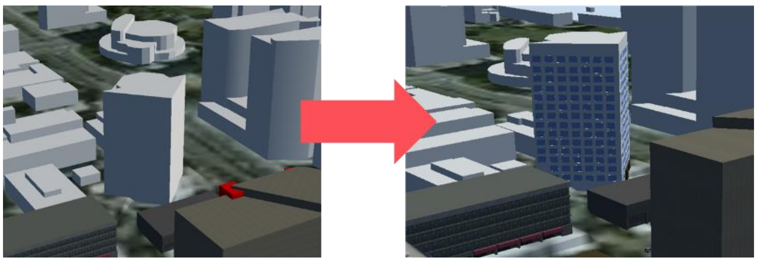

Figure 9. 3D scene improvement.

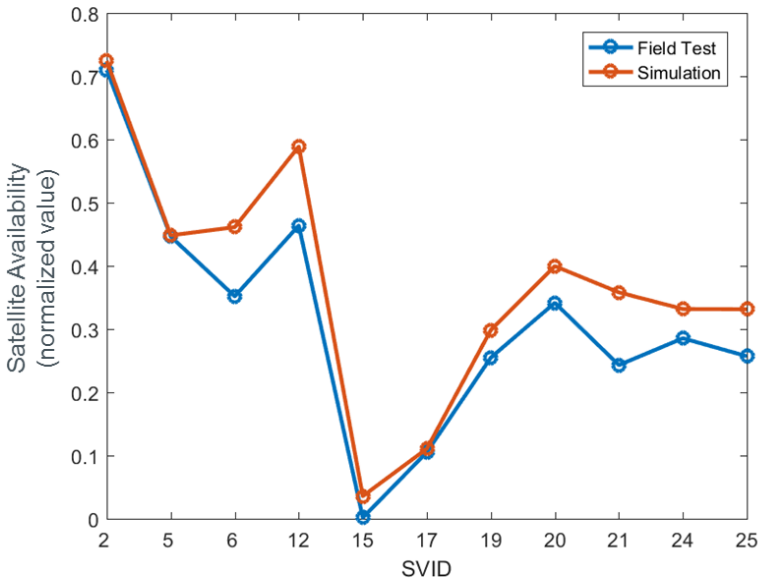

Figure 10. Satellite availability for field data (blue) and simulation after scene improvement.

SAN JOSE DYNAMIC - RESULTS

Similar results were obtained with the dynamic test in San Jose. Figure 11 shows the results obtained for satellite PRN12 (a-c) and PRN24 (d-f). The figure shows the carrier-to-noise (C/N_0) ratio (a, d), pseudorange residual (b, e), and Doppler residual (c, f) for field test (blue line) and simulation (red line). The walking trajectory included two moments where the antenna was stopped because of a traffic light. Those moments correspond to a relatively flat C/N_0 that can be clearly seen in the field test and simulation data for both PRNs. When, instead, the antenna was moving a higher variation in the C/N_0 is noticeable in both simulation and field-test.

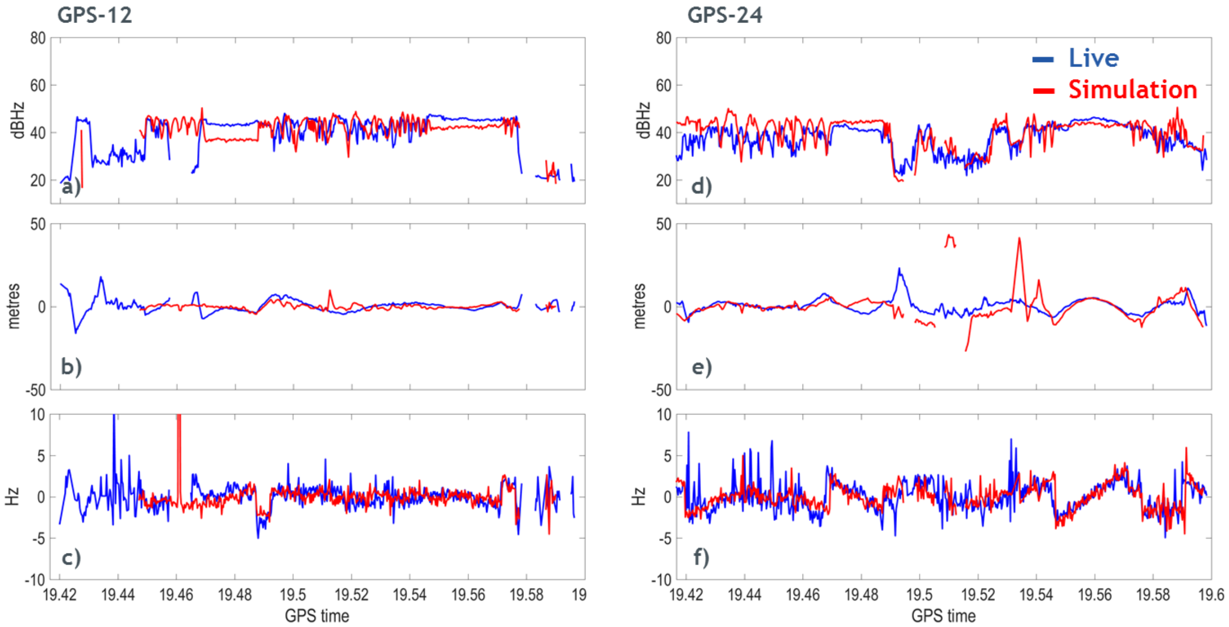

Figure 11. Carrier-to-Noise ratio (top), pseudorange residual (middle), and doppler residual (bottom) for PRN 12 (left column) and PRN 24 (right column).

Figure 12a illustrates the positioning error obtained from simulated (red) and field test (blue). The first part of the simulation produced an error that is smaller than the one obtained from field data. However, from the hour 19.48 a good agreement can be seen. The satellite availability is also shown in Figure 12b. This last result was obtained with the improved model described in Figure 9.

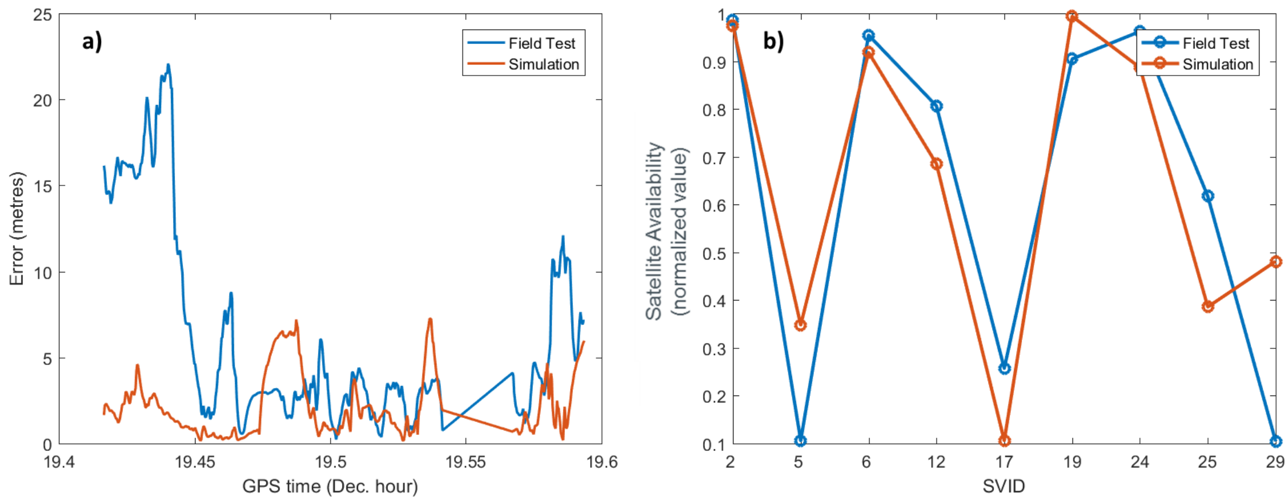

Figure 12. (a) Positioning error for field-test (blue) and simulation (red); (b) Satellite availability for field data (blue) and simulation (red) after scene improvement.

CONCLUSIONS AND FUTURE WORK

The objective of this paper was to show some first results of a new simulation system for multipath. The system is designed to generate realistic multipath that depends on time, position, and type of urban environment. The 3D scene is used to calculate the multipath (reflection and diffraction) caused by the buildings around the antenna.

The paper demonstrated that realistic multipath can be generated by simulating reflections and diffractions even with a simple 3D model. However, the inclusion of finer details in the model can improve the simulation and make it even closer to reality. As always, simulation interest is a tradeoff between reliability in all conditions and efforts to adapt (i.e. to specify) a generic and simple model. The added value of our model consists in its simplicity and its good compliance with field data.

Ray Tracing technics coupled with Geometrical Optics and Uniform Theory of Diffraction are relevant and simple methods to simulate the propagation of GNSS signals in complex urban environment. This paper showed a good agreement between simulation and field measurements. Some discrepancies still exist and are due to the limitations of such a model:

- The accuracy of the model is never perfect and, as Ray Tracing is a deterministic method, the returned results strongly depends on the quality of the input data used to generate the model.
- Geometrical Optics is a simple (but efficient) method. Only specular rays are modelled thus the system won't be able to generate all the signals coming from other phenomena such as scattering. Another limitation is given by the hardware. In fact, the number of simulated multipath depends on the number of available channels in the simulator.
- The simulation parameters try to mimic the field conditions. However, the simulated trajectory is approximated, and other factors like pedestrian, vegetation (isolated trees or forest), and traffic may contribute to reduce some of the discrepancies that can be observed between simulation and field-test.

All these limitations can explain the differences between simulated and measured data. Currently, the impact of vegetation (forest and/or isolated trees) models, pedestrian motion, and traffic on the multipath signal is under investigation.

ACKNOWLEDGMENTS

We would like to acknowledge Colin Ford and Ajay Vemuru from Spirent Communications and Antoine Boudet, Yann Dupuy, Arnold Duquesne, and Paul Pitot from OKTAL Synthetic Environment.

REFERENCES

[1] L. Wang, P. Groves, and M. Ziebart, "Multi-constellation GNSS performance evaluation for urban canyons using large virtual reality city models," *J. Navig.*, vol. 65, no. 3, pp. 459–476, 2012.

[2] J. Bradbury, M. Ziebart, P. Cross, and P. Boulton, "Code multipath modelling in the urban environment using large virtual reality city models: Determining the local environment," *J. Navig.*, vol. 60, pp. 95–105, 2007.

[3] J. Bradbury, "Prediction of urban GNSS availability and signal degradation using virtual reality city models," in *Proceedings of the 20th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2007)*, 2007, vol. 3, pp. 2696–2706.

[4] A. Bourdeau, M. Sahmoudi, and J.-Y. Tourneret, "Constructive use of GNSS NLOS-multipath: Augmenting the navigation Kalman filter with a 3D model of the environment," in *Information Fusion (FUSION), 2012 15th International Conference on*, 2012, pp. 2271–2276.

[5] P. François, B. David, and M. Florian, "Non-Line-Of-Sight GNSS signal detection using an on-board 3D model of buildings," in *ITS Telecommunications (ITST), 2011 11th International Conference on*, 2011, pp. 280–286.

[6] K. Ahmad and M. Sahmoudi, "Reliable GNSS positioning in mixed LOS/NLOS environments using a 3D model," in *ENC 2013*, 2013.

[7] M. Obst, S. Bauer, and G. Wanielik, "Urban multipath detection and mitigation with dynamic 3D maps for reliable land vehicle localization," in *Proceedings of IEEE/ION PLANS*, 2012.

[8] A. Bourdeau, M. Sahmoudi, and J.-Y. Tourneret, "Prediction of GNSS Signal Bias Using a 3D Model in Urban Environments," in *Proc. European Navigation Conference (ENC 2012)*, 2013.