Simulation of an Indoor GNSS Receiver Based on Semi-Analytical Modelling

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BIOGRAPHY

Zoran Dobrosavljevic was born in 1961 in Velika Plana, Serbia. He got his BSEE (1986), MSc (1991) and PhD (1995) in the area of telecommunications from the School of Electrical Engineering, University of Belgrade, Serbia. Zoran was with the Department of Telecommunications at the University of Belgrade between 1986 and 2001, first as a research assistant and then as an assistant professor where he worked in the areas of mobile communications, radars and digital signal processing. In 2001, Zoran joined Roke Manor Research Ltd., in Romsey, Hampshire, UK as a consultant engineer. His interests lie in the areas of satellite navigation, mobile communications and adaptive signal processing. Zoran has published and presented over 60 technical papers in the aforementioned fields of engineering. He is also co-author of a textbook on digital signal processing that is currently being used as part of an undergraduate course at the School of Electrical Engineering, University of Belgrade, Serbia.

Arun Arumugam was born in 1977 in Penang, Malaysia. He obtained his BEng (1999) and PhD (2004) in the area of wireless communications from the Department of Electrical and Electronics Engineering, University of Bristol, UK. Arun began his career at Roke Manor Research Ltd., in Romsey, Hampshire, UK as an engineer in 2005. His interests lie in the areas of mobile communications and in particular, wireless local area networks and personal area networks technology, satellite navigation and systems engineering. He has published and presented a number of conference and journal papers. Arun was also the recipient of the IEE[1] Robinson Research Fellowship Award in 2000 and the IEEE Chester-Saal Award in 2002.

1. INTRODUCTION

Personal navigation and location based services using satellite navigation has gained worldwide popularity in recent years. This has been fueled by an increase in the number of consumer electronic devices in the marketplace, such as mobile phones, PDAs and popular in-car navigation systems that come equipped with GNSS receivers. As these devices become increasingly popular in the marketplace, their uses will inevitably extend towards more challenging environments such as shopping malls, urban canyons and office buildings. Subsequently, the ability of GNSS-enabled personal devices to receive satellite signals and give precise positioning information becomes important. Since the radio environment is far from ideal at urban and indoor locations, the modelling concepts and algorithms applied in GNSS simulations can become quite complex. Consequently, the design and development of modern commercial GNSS receivers increasingly depends on reliable, accurate and reasonably fast software simulation tool kits.

Traditional GNSS system simulations are based on Monte Carlo approach as this method is especially useful in the analysis and study of systems that are strongly nonlinear, with large uncertainties and or variation in the input parameters. However, a primary disadvantage of Monte Carlo approach is that models are often numerically intensive. For example, in order to capture several minutes worth of real-time performance of a GNSS receiver, a typical ‘direct approach’ Monte Carlo simulation may require several hours of processing time. This can be further exacerbated if the model includes complex algorithms needed to acquire and track weaker signals.

This paper describes a novel semi-analytical approach in modelling a GNSS receiver for indoor operation. Contrary to Monte Carlo, this approach is based on direct modelling of correlation functions of the satellite navigation waveforms. Consequently, a significant reduction in simulation time (typically by several orders of magnitude) can be attained and hence, it is possible for the simulation to run in real or near-real time on standard ‘off the shelf’ desktop PCs. This makes it possible to analyse long-term effects such as changes in satellite constellation, diurnal changes in ionosphere propagation or long-term changes in local multipath environment.

This paper is organised as follows; Section 2 describes the GNSS simulation model implemented. The semi-analytical approach implemented here compared to a typical Monte Carlo simulation are highlighted in Section 3. Sections 4 and 5

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[1] Currently known as the Institution of Engineering and Technology (IET), UK.

describe the code tracking loop and the signal structure as modelled using this approach. Section 6 briefly describes the state machine status and the relationship between signal acquisition and carrier tracking. Section 7 presents a number of results and Section 8 verifies the simulation model and results obtained. Several conclusions are drawn in Section 9.

2. AN OVERVIEW OF THE GNSS RECEIVER MODEL

A satellite navigation system was modelled containing a combination of GPS and Galileo satellite signals. The aim of the simulation was to obtain the pseudorange error performance of a mass-market GNSS receiver in an indoor and/or urban environment. Figure 1 shows a block diagram of the GNSS receiver simulation chain.

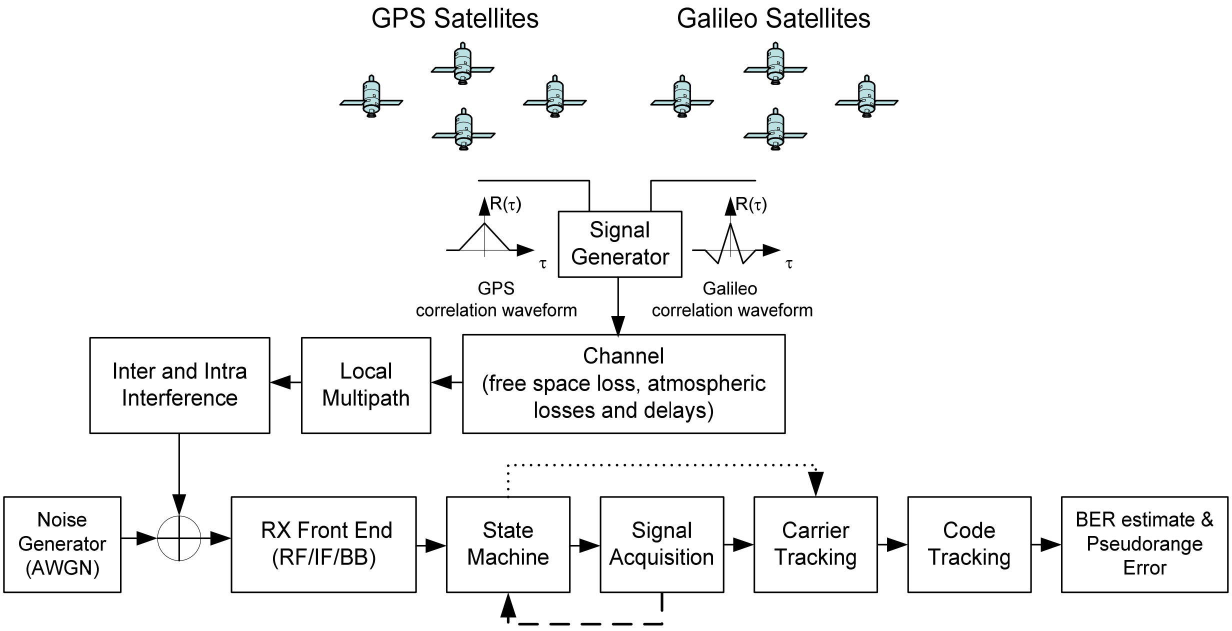

Figure 1 : GNSS simulation block diagram

The GNSS simulation was organised as a collection of modules (within a simulation library) in the order of processes shown in Figure 1. Each module takes an input signal from the preceding module, performs a transformation on it and feeds the transformed signal into the next module. Signal transformation is controlled by a set of configurable parameters. A typical module is illustrated in Figure 2.

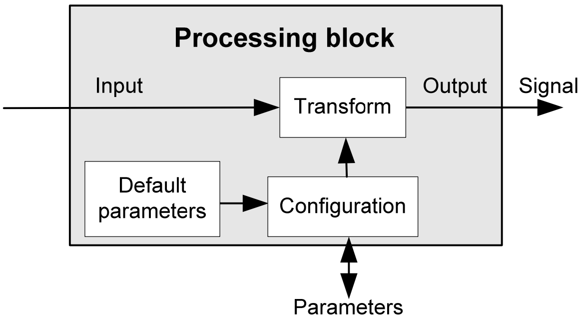

Figure 2 : A single simulation module

Simulation modules are stored in a library, and have to be connected into a simulation chain in order to run a simulation. The chain of modules is invoked from the main simulation.

The pseudorange error performance was obtained by addressing the effects of local environment (building penetration loss, strong indoor multipath etc.) in a module separately from the general channel effects (path loss, atmospheric loss, ionospheric and tropospheric delays etc. The local multipath model was based on Roke's proprietary Epsilon [Ref 2] propagation model. Interference between the satellites belonging to one navigation system as well as the interference between different systems has also been included in the model.

The receiver front end concentrates on the effects of band limiting, thermal noise, various implementation losses and effects of analogue to digital conversion (ADC). The digital part of the receiver includes signal acquisition and tracking of multiple signals. The state of individual receive channels is under control of a dedicated state machine. Finally, the output of the simulation produces pseudorange error and bit error rate (BER) performance.

3. SEMI-ANALYTICAL APPROACH OF THE SIMULATION CONCEPT COMPARED TO MONTE CARLO SIMULATION

The differences between standard Monte Carlo approach and the simulation concept that was developed for the GNSS simulation can be observed in the structure and function of modules, as well as the way the signals passing through the modules are represented.

3.1. Modules

In a Monte Carlo simulation, each module in the simulation models the effects that the corresponding block in the modelled system has on the signal passing through that stage. For example, an amplifier would amplify the signal, add some noise to it, and distort it if the input signal is too strong. The signal is passed from one module to another in the chain, and the simulation output is obtained at the output of the last module in the chain, as a result of the combination of effects that individual modules have on the intermediate signals.

More importantly, signal transformation in the block has to be implemented in a way in which that block would transform the processed signal, irrespective of whether further processing would diminish the importance of the applied signal transformation. For example, an anti-aliasing filter preceding an ADC may typically be modelled using a standard “filter” module with high numerical accuracy, although that filter may be immediately followed by a single-bit ADC that will strip any information of the signal amplitude and reduce each sample to its sign only.

In the semi-analytical approach, a module is modelled only to an extent that it has an effect on the simulation output. In this case, if the simulation targets the shape of the correlation function of the output signal, the module will only model those effects of the signal processing block that have a direct impact on that function. All other effects will either be excluded from the model, or treated as ‘second-class’ effects, i.e. replaced with simplified models representing the effects that they have on the output. This simplification can be obtained either analytically (hence, the term ‘semi-analytical’), or from a stand-alone simplified Monte Carlo simulation that concentrates on the block in question. Through this simplification, significant reduction in simulation complexity and execution time can be achieved; e.g. a single-bit ADC processing a spread-spectrum signal can be replaced by quantisation noise in the de-spread signal.

The downside of semi-analytical modelling lies in the assumption that effects that individual modules have on the output signal may be treated in isolation. In other words, the simulated system is ‘weakly connected’, which means that the system operates in a regime that it has been designed for. This implies that a radical change in the simulated system is easier to implement on a Monte Carlo simulation than a semi-analytical model. Thus, if we are later interested in how a receiver would work in the presence of strong interference, all we need to do in a Monte Carlo model is to write a module that would generate that strong interference and include it in the simulation chain. In a semi-analytical model, we have to consider how each module would behave in the presence of such new signal and modify some of the modules accordingly as deemed necessary.

3.2. Signals

The difference between the two simulation approaches exists in the realm of simulated signals too. In the Monte Carlo simulation, the signal is a true representation of the signal a particular block processes (with the simplification of using analytical signals for modulated signals). In the semi-analytical simulation, the signal modelled is the simulation output. In the GNSS simulation in question, this signal is the autocorrelation function. That function is distorted by individual simulation modules in the same way the distortion of the signal by the corresponding block in the real receiver would affect the correlation function.

4. CODE TRACKING LOOP

The differences between the semi-analytical model implemented here and a typical Monte Carlo simulation approach can be realised by analysing the approach taken to simulate the spreading code tracking loop. A typical code tracking loop in a GNSS receiver is an early-late (E-L) loop as shown in Figure 3. The loop consists of the demodulator, multiplication with the local sequence for three different timing offsets of the locally generated code (early, punctual and late: E, P, L), integrate and dump circuits and the actual code loop discriminator. A Monte Carlo simulation would need to simulate all the blocks shown in the figure in order to model the loop performance.

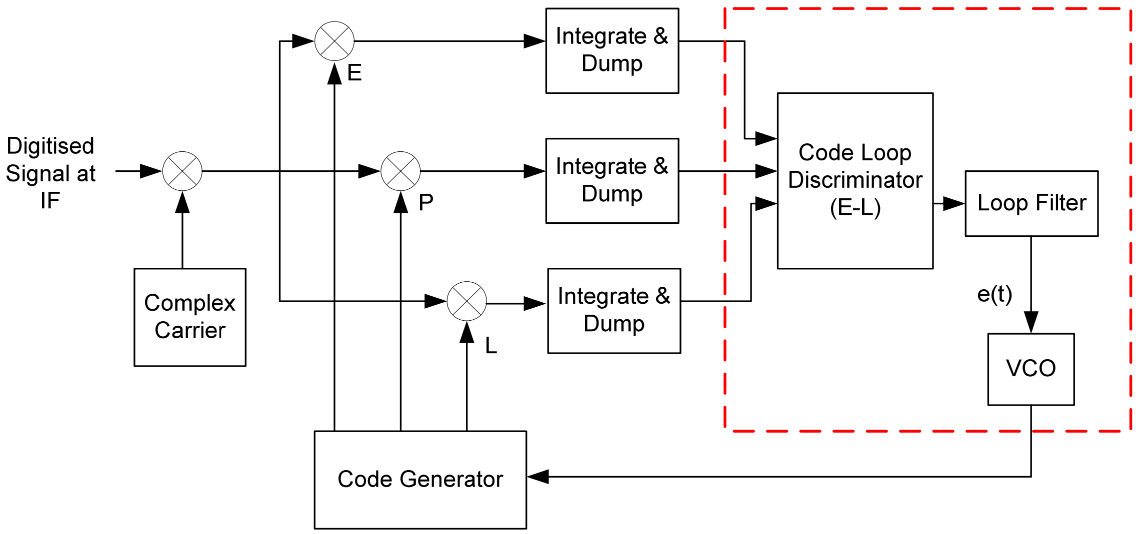

Figure 3 : Block diagram of the code tracking loop

In a semi-analytical approach, the shape of the correlation function is modelled; therefore the signals at the outputs of E, P and L integrate and dump circuits are already available as corresponding correlation function samples. Therefore, the model only needs to include part of the code tracking loop enclosed in the bold red line. Omission of the significant part of the loop running on spreading code rate, and modelling only the part whose speed of response is essentially defined by loop filters and loop gain means that the sampling rate used in the software model can be drastically reduced.

5. SIGNAL MODEL

The semi-analytical model of the code tracking loop described in the previous section implies that the simulation models autocorrelation functions instead of signal waveforms. The autocorrelation function model used in the semi-analytical simulation of the GNSS system is shown in Figure 4 for GPS C/A signal.

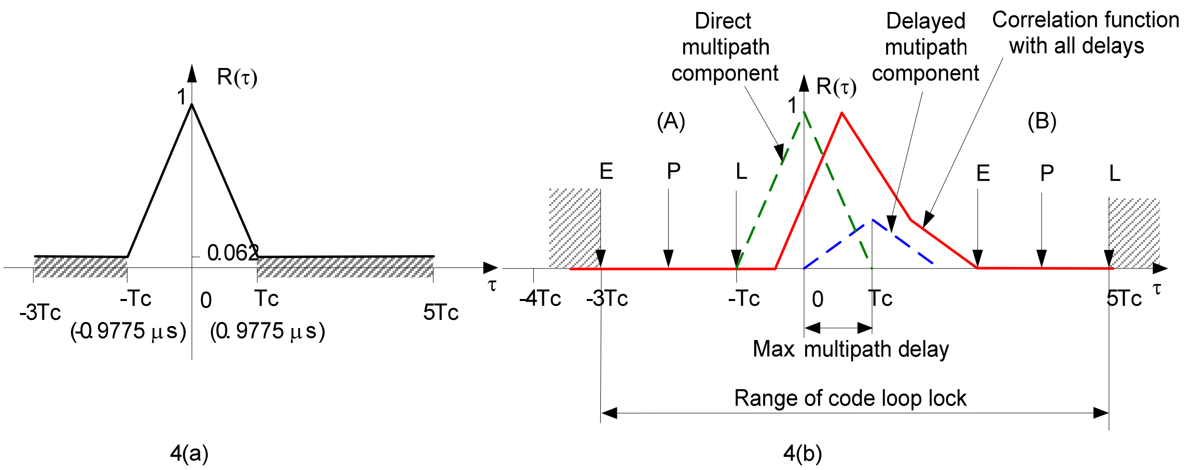

Figure 4 : GPS correlation function used as the input signal in the simulation

The generic model of a GPS C/A correlation function that does not specify the particular SV code is shown in Figure 4(a). The detailed structure of sidelobes that is dependent on the code is treated as a parameter of secondary importance in the simulation. Therefore, instead of modelling the exact shape of the sidelobes, they are included in the simulation in the following way:

- In the autocorrelation function, the sidelobes are represented as a pedestal 24 dB below the autocorrelation peak, as shown in Figure 4(a). This is seen as suitable because the accurate structure of sidelobes will have a negligible influence on simulation results since GPS signals are buried in noise;

- Cross-correlation between different codes (i.e. inter and intra-system interference between the individual satellite signals) is represented as additive noise; power of that noise depends on the instantaneous power of interfering signals in the simulation.

Additional improvement in the simulation time was achieved through modelling only the central part of the correlation functions; i.e. instead of modelling the signals for all possible spreading code chip offsets (-511…+512 chips), only the window of delays (-3…+5 chips) was modelled, as shown in Figure 4(b). The reasons that justify this reduction of modelled signal length are:

- When the receiver is in the 'tracking' mode, the code tracking loop is locked on the correlation peak. If the tracking loop moves away from the correlation peak, the receiver will lose lock to that satellite and will switch to 'acquisition' mode;
- The widest meaningful spacing between the 'E' (Early) and 'L' (Late) branches in the code tracking loop is $2T_c$, where T_c stands for chip duration;
- The maximum realistic multipath delay for simulated scenarios is less than 1μs, which corresponds to 300m of path difference, or one chip length only;
- All additional delays in the simulation system (e.g. ionosphere, troposphere and filters in the receiver front-end are expected to be less than $1T_c$.

The combination of all multipath and all delays on an idealised shape of the correlation function are shown in Figure 4(b). This figure also shows two extreme possible positions of early, punctual and late samples in the code tracking loop; if the loop moves further away from the shown locations of pointers, the receiver will switch to the acquisition mode. With the correlation peak width being $(-T_c\ldots+T_c)$, and all delays and multipath amounting to maximally $2T_c$, the distorted correlation peak in the simulation has to be located within the interval $(-T_c\ldots+3T_c)$. The distance between the early and late code offsets in the code tracking loop is limited to $2T_c$ by the system design. Therefore, the window of delays that can possibly happen in the simulation is limited to $(-3T_c\ldots+5T_c)$, as shown in Figure 4(b).

6. STATE MACHINE MODEL

The term "state machine" is used here as a description of the state the receiver is in regarding the reception of signals coming from individual satellites. A GNSS receiver can be in one of several states, depending on the presence of satellite signals, status of carrier and code lock loops, and availability of the ephemeris and the almanac data. The state of the receiver can be different for different satellites; i.e. the receiver may track some satellites while acquiring others. Therefore, the number of state machines in a receiver depends on the number of signal receive channels.

The GNSS simulation has implemented the state machine with acquisition and tracking states, as shown in Figure 5.

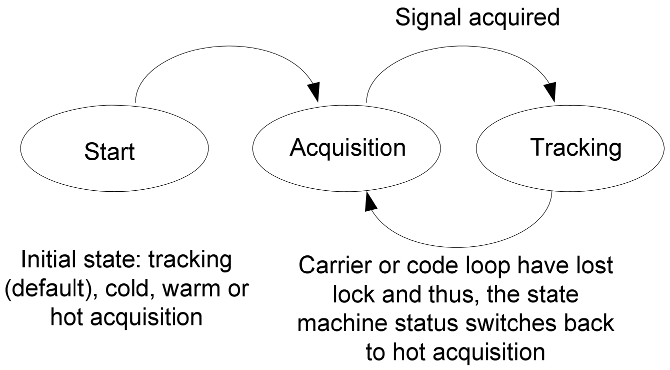

Figure 5 : State machine

The initial state "Start" shown in Figure 5 marks the start of the simulation. This is to indicate that the initial state of each simulated state machine can be one of the following:

- Tracking (default);
- Hot acquisition;
- Warm acquisition;
- Cold acquisition.

The initial state of the state machine has a major influence on the amount of simulation time that has to pass before the receiver acquires lock and simulation starts to produce pseudorange estimates. Probabilities of transitions between the individual states of the state machine depend on various simulation parameters. For example, the transition from 'acquisition' to 'tracking' happens during simulation as the receiver detects and locks the spreading code and carrier and acquires the data. The transition back to acquisition happens when one of the tracking loops loses the lock and the probability of this happening depends on the SNR, channel fading, multipath etc.

7. SIMULATION RESULTS

The simulation was run using a set of default parameters stored in the configuration file. These values were recommended values and are reconfigurable. Figure 6 shows plots for GPS and Galileo satellites and the measured pseudorange error (in meters), the satellite visibility status, state machine status and also the code and carrier loop lock status.

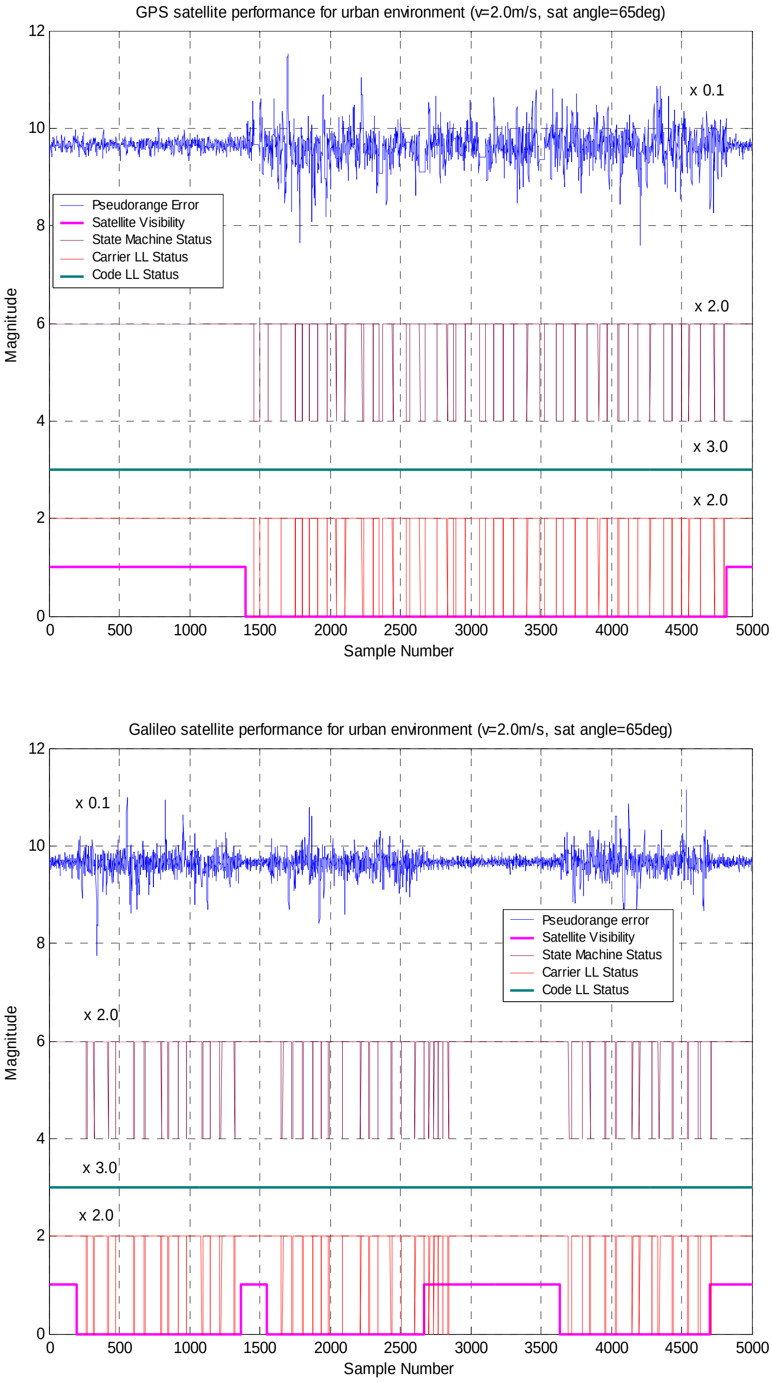

Figure 6 : Pseudorange error, satellite visibility and loop lock statuses for GPS and Galileo for urban

For visual convenience, the pseudorange error has been multiplied by 10, the state machine status by a factor of 2 (so 6 means 'tracking', 4 means 'hot acquisition' status), the carrier loop lock status by a factor of 2 and the code loop lock status by a factor of 1.5. In this manner, all 5 plots can be seen on the same graph and same scales.

From the plots shown, it can be observed that the satellite visibility obtained from the simulation (5000 iterations, i.e. 20 seconds of simulation time) clearly resembles the satellite being visible at some instances and not at other times. This is because for an urban environment, the satellite visibility may be in non-LOS due to the presence of tall buildings and as a result, the signal may be lost. When the signal is lost, the tracking loops lose lock on the signal and the state machine status changes from "tracking" to "hot acquisition".

The receiver performance for an indoor environment is shown in Figure 7. Since the signal enters through a window and the windows are only on one side of the room, we would expect that the satellite would be visible for approximately 25% of the time over an extended duration of time. The trend can be observed from Figure 7.

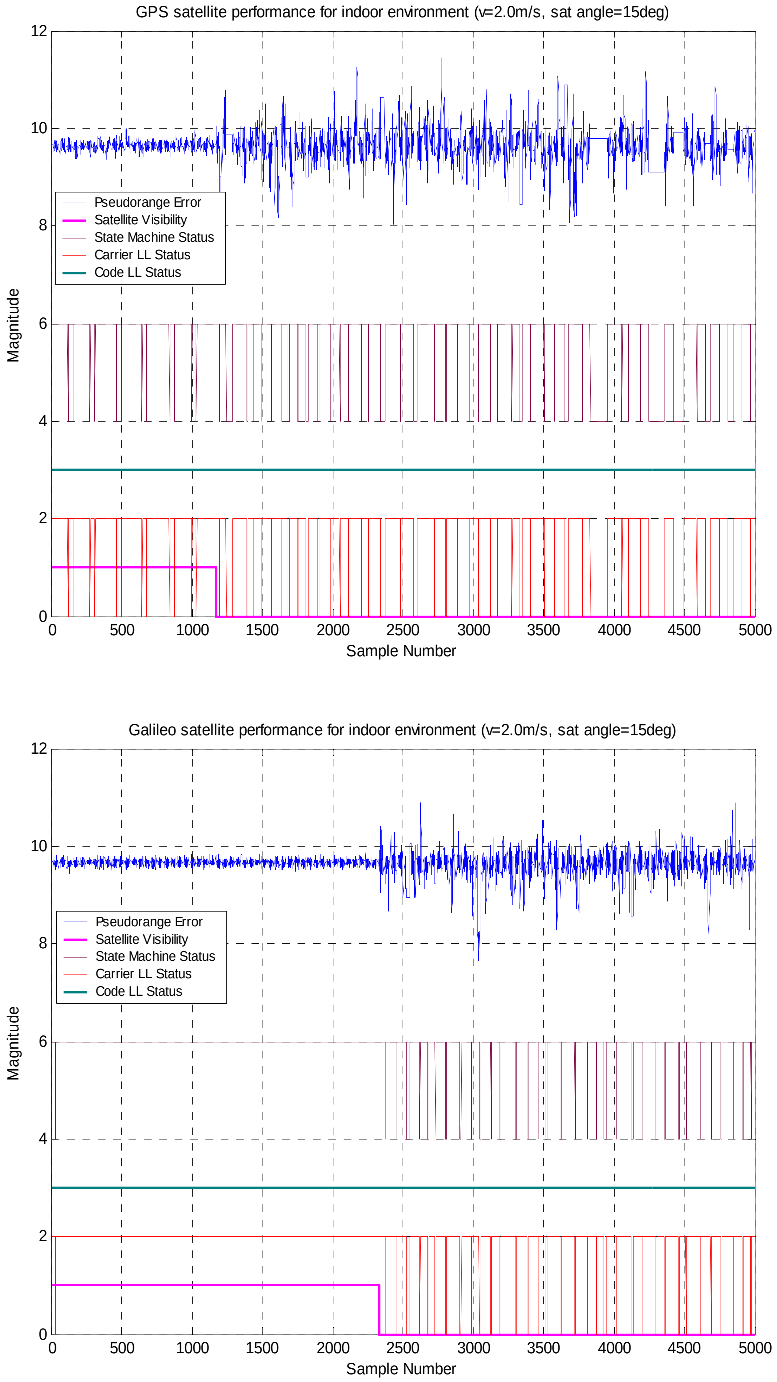

Figure 7 : Pseudorange error, satellite visibility and loop lock statuses for GPS and Galileo for indoors

8. SOFTWARE VERIFICATION

The developed software modules were tested rigorously, some as stand alone units and others in combination with previously tested modules. Once the functionality of the individual modules was verified, the whole system was integrated into a full simulation chain.

The simulation acceptance tests comprised 6 tests, three for GPS and three for Galileo scenarios. These tests were designed to verify the sensitivity, nominal accuracy and multipath performance of the two GNSS systems. These tests are based on UMTS FDD assisted GPS terminal conformance specification TS 134 171 in [Ref 3], Section 5 ("Performance Requirements for A-GPS"). For each test, the pseudorange error performance was compared against the minimum performance recommended in [Ref 3], Section 5. Table 1 lists results of the aforementioned acceptance tests. The values tabulated are the r.m.s. pseudorange error measured in meters.

Test	**GPS Simulated System**	**GALILEO Simulated System**	**Expected results as recommended in [Ref 3]**
Sensitivity	29.2 m	21.6 m	< 50 m
Nominal Accuracy	9.4 m	6.9 m	< 15 m
Multipath Performance			< 50 m on the first three satellites
Satellite 1	8.9 m	6.9 m	
Satellite 2	8.9 m	6.7 m	
Satellite 3	40.2 m	12.3 m	
Satellite 4	40.7 m	12.0 m	
Satellite 5	40.4 m	11.9 m	

Table 1 : Pseudorange error performance for the acceptance test for GPS and Galileo satellites

9. CONCLUSIONS

This paper describes a novel semi-analytical approach in modelling a GNSS receiver for indoor operation. The GNSS simulation comprised a combination of GPS and Galileo satelites. The simulation concept was based on a semi-analytical approach. The differences between a typical Monte Carlo simulation approach and a semi-analytical approach as implemented here were highlighted and discussed with particular reference to a code tracking loop. It was found that due to the reduced complexity of the semi-analytical approach, the simulation was able to run in near-real time. The GNSS simulation results were validated against results for a UMTS FDD assisted GPS terminal recommended in the conformance specifications by ETSI TS 134 171. The simulation results were verified successfully and fell within the recommended range. Finally, whilst there are significant benefits of the semi-analytical approach, there are also some limitations particularly for systems whereby the modules are 'strongly connected'. In these cases, the semi-analytical approach may warrant further expansion in order to improve on its efficiency.

10. ACKNOWLEDGEMENTS

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11. REFERENCES

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[Ref 2] Fisher J., Simpson S.H.W., Welsh T., "An Urban Canyon Multipath Model for Galileo", The European Navigation Conference GNSS2002, Copenhagen, Denmark, May 2002.

[Ref 3] ETSI TS 134 171 V6.1.0 (2005-10) Technical Specification: Universal Mobile Telecommunications System (UMTS); Terminal conformance specification; Assisted Global Positioning System (A-GPS); Frequency Division Duplex (FDD) (3GPP TS 34.171 version 6.1.0 Release 6)