New GNSS Signals Demodulation Performance in Urban Environments

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BIOGRAPHIES

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Lionel RIES is head of the localization / navigation signal department in CNES, the French Space Agency. The department activities cover signal processing, receivers and payload regarding localization and navigation systems including GNSS (Galileo, GNSS space receivers), Search & Rescue by satellite (SARSAT,MEOSAR), and Argos (Environment Data Collect and Location by Satellite). He also coordinates for CNES, research activities for future location / navigation signals, user segments equipment and payloads.

Charly Poulliat received the Eng. degree in Electrical Engineering from ENSEA, Cergy-Pontoise, France, and the M.Sc. degree in Signal and Image Processing from the University of Cergy-Pontoise, both in June 2001. From Sept. 2001 to October 2004, he was a PhD student at ENSEA/University Of Cergy-Pontoise/CNRS and received the Ph.D. degree in Signal Processing for Digital Communications from the University of Cergy-Pontoise. From 2004 to 2005, he was a post-doctoral researcher at UH coding group, University of Hawaii at Manoa. In 2005, he joined the Signal and Telecommunications department of the engineering school ENSEA as an Assistant Professor. He obtained the habilitation degree (HDR) from the University of Cergy-Pontoise in 2010. Since Sept. 2011, he has been a full Professor with the National Polytechnic Institute of Toulouse (University of Toulouse, INP-ENSEEIHT). His research interests are signal processing for digital communications, error-control coding and resource allocation.

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ABSTRACT

Satellite navigation signals demodulation performance is historically tested and compared in the Additive White Gaussian Noise propagation channel model which well simulates the signal reception in open areas. Nowadays, the majority of new applications targets dynamic users in urban environments; therefore the implementation of a simulation tool able to provide realistic GNSS signal demodulation performance in obstructed propagation channels has become mandatory. This paper presents the simulator SiGMeP (Simulator for GNSS Message

Performance), which is wanted to provide demodulation performance of any GNSS signals in urban environment, as faithfully of reality as possible. The demodulation performance of GPS L1C simulated with SiGMeP in the AWGN propagation channel model, in the Prieto propagation channel model (narrowband Land Mobile Satellite model in urban configuration) and in the DLR channel model (wideband Land Mobile Satellite model in urban configuration) are computed and compared one to the other. The demodulation performance for both LMS channel models is calculated using a new methodology better adapted to urban environments, and the impact of the received signal phase estimation residual errors has been taken into account (ideal estimation is compared with PLL tracking). Finally, a refined figure of merit used to represent GNSS signals demodulation performance in urban environment is proposed.

INTRODUCTION

Global Navigation Satellite Systems (GNSS) are increasingly present in our everyday life. The interest of new users with further operational needs implies a constant evolution of the current GNSS systems. A significant part of the new applications are found in environments with difficult reception conditions such as urban or indoor areas. In these obstructed environments, the received signal is severely impacted by obstacles which generate fast variations of the received signal's phase and amplitude that are detrimental to both the ranging and demodulation capability of the receiver. One option to deal with these constraints is to consider enhancements to the current GNSS systems, where the design of an innovative signal more robust than the existing ones to distortions due to urban environments is one of the main aspects to be pursued. A research axis to make a signal more robust, which was already explored, is the design of new modulations adapted to GNSS needs that allows better ranging capabilities even in difficult environments [1][2]. However, other interesting axes remain to be fully explored such as the channel coding of the transmitted useful information: users could access the message content even when the signal reception is difficult.

Computer simulations based on realistic received signal models are widely used in order to provide a first strong validation of the demodulation performance of the newly designed signal. In this respect, the aim of this paper is to provide a software simulation tool able to compute the demodulation performance of any GNSS signals in a realistic urban Land Mobile Satellite (LMS) channel model. In this way, the demodulation performance in urban environments of the newly designed GNSS signal can be simulated and compared with the existing ones. The simulator is referred as Simulator for GNSS Message Performance (SiGMeP).

Two different LMS channel models have been identified and implemented in the simulator: the Prieto channel model, a narrowband model which considers that all the multipath echoes are received at the same time than the direct signal, and the DLR channel model, a wideband model which takes into account the time delays between the direct signal and the multipath echoes. GNSS signals demodulation performance provided in this paper have been calculated using the two channel models. As a consequence, a first comparison between the impact on the demodulation performance between the use of a narrowband and a wideband channel model can be made.

The demodulation performance has been computed using a new methodology more adapted to signal transmissions in urban environments. The navigation message error probability is no longer computed as a function of the received C/N_0 as it is generally made in GNSS, but as a function of the C_{LOS}/N_0 which considers a signal reception without propagation channel impact. This term C_{LOS}/N_0 being linked to the satellite elevation angle, the navigation message error probability will be directly represented as a function of the satellite elevation angle.

Moreover an advanced figure of merit is defined to represent the specific GNSS signals demodulation needs and it provides more detailed demodulation performance information in urban environments. This figure of merit consists in showing the demodulation performance computed in a particular signal reception condition, usually in a condition providing a higher probability of demodulation success, altogether with statistical results concerning the time periods between these good signal reception condition episodes.

The paper is thus organized as follows. Section I describes the two propagation channel models used in the simulation tool SiGMeP. Section II presents the SiGMeP structure. Section III details the new proposed methodology developed with the objective of adapting the computation of the GNSS signals demodulation performance in urban environments. The first steps of this new approach are showed in section IV, providing refined demodulation performance for GPS L1C simulated with narrowband and wideband LMS channel models. These results take into account the impact of the Phase-Locked Loop (PLL) on the signal carrier phase estimation process. And the additional figure of merit is showed and detailed for the Prieto channel model case.

I- URBAN LMS CHANNEL MODELS

The propagation channel mathematical model is the key element of the simulation because it has to be correctly modeled in order to obtain a faithful representation of the environment impact on the received signal. In an urban environment, the propagation channel is called LMS channel.

The channel model state-of-the-art analysis shows that two models are mostly used for GNSS performance simulations: the narrowband model designed by F. Perez-

Fontan in the early 2000 [3][4] and improved by R. Prieto-Cerdeira in 2010 [5], and the wideband model designed by the DLR (the German Aerospace Center) in 2002 [6].

1) Channel Impulse Response (CIR)

The impact of the LMS propagation channel on the received signal can be modeled using a channel time-variant impulse response (CIR):

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

Where:

- $r(t)$ is the received signal at instant t,
- $s(t)$ is the transmitted signal at instant t,
- $h(t;\tau)$ is the channel time-variant impulse response,
- t is the variable determining the instant of time at which the CIR is defined,
- τ is the variable which determines the delay at which the CIR is defined.

Therefore, the CIR mathematical expression depends on the selected channel model, Prieto or DLR.

2) Narrowband Model

The Perez-Fontan Model Base

The Perez-Fontan model is narrowband, meaning that the delay of the direct signal and the delays of the multipath echoes are assumed to be equal. The CIR is thus modeled as in (2):

$$h(t;\tau) = c(t)\delta\big(t - \tau_{direct}(t)\big) \quad (2)$$

Where:

- $c(t) = a_{received}(t)e^{j\varphi_{received}(t)}$ represents the channel attenuation and phase with $a_{received}(t)$ the received signal complex envelope.

The Perez-Fontan model is a statistical model based on measurement campaigns carried out in the 90s. The measurement campaign allowed modeling the received signal complex envelope distribution with a Loo distribution.

Loo distribution: The complex envelope $a_{received}(t)$ of the overall received signal can be divided into two components, the direct signal and the multipath components:

$$a_{received}(t) = a_{direct}(t)e^{j\varphi_{direct}(t)} + a_{multipath}(t)e^{j\varphi_{multipath}(t)} \quad (3)$$

Where:

- $a_{direct}(t)$ is the direct signal component amplitude and $\varphi_{direct}(t)$ is its Doppler phase,
- $a_{multipath}(t)$ is the multipath component amplitude and $\varphi_{multipath}(t)$ is its phase.

The direct signal component corresponds to the Line-Of-Sight (LOS) signal which can be potentially shadowed or blocked. The multipath component corresponds to the sum of all the reflections/refractions of the transmitted signal found at the RF block output.

The distribution of the Loo parameters is defined as follows [3]:

- The amplitude of the direct signal component $a_{direct}(t)$ follows a Log-Normal distribution, characterized by its mean α_{dB} and its standard deviation Ψ_{dB},
- The amplitude of the multipath component $a_{multipath}(t)$ follows a Rayleigh distribution, with a standard deviation σ. The value of σ is calculated from the average multipath power with respect to an unblocked LOS signal: MP_{dB} (4). MP_{dB} is the parameter provided in the literature.

$$\sigma = \sqrt{10^{\frac{MP_{dB}}{10}}/2} \quad (4)$$

Therefore, the set of parameters (α_{dB}, Ψ_{dB}, MP_{dB}) completely defines the Loo distribution and is referred as the Loo parameters. They depend on the environmental conditions:

- The type of environment (semi-urban, urban, deep urban…),
- The satellite elevation angle,
- The signal carrier band,
- The channel states.

The generation of this Loo distribution is illustrated in **Figure 1**.

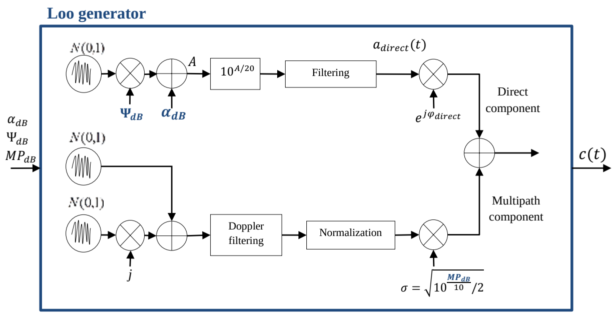

Figure 1: Generation of samples following a Loo distribution

Slow and fast variations: The two signal components constituting the received signal have different variation rates. In other words, the minimum length (or time if converting the length by using the user velocity) between two uncorrelated samples of a component is different for each component. The direct signal component variation rate is slower than the multipath component variation rate.

For a Log-Normal variable corresponding to the direct signal component, the minimum length separating two uncorrelated samples is referred as the correlation distance l_{corr}. The correlation distance is equal to 1 m for S-band and 2 m for L-band according to [5].

For the Rayleigh variables corresponding to the multipath component, the minimum length between two uncorrelated samples when the user is static is usually set in the literature to λ/4 meters [7], where λ is the wavelength of the carrier. But in fact, a minimum length of at least λ/8 meters is usually selected [4] to ensure the uncorrelation property for more strict interpretations. When the user is in motion, the minimum length depends on the user velocity and thus this length is usually expressed in time. Moreover, although the minimum length definition varies in the literature, the component complex envelope variation in the time domain is well defined and determined by the received signal Doppler spread B_d. The Doppler spread represents the bandwidth occupied by the different Doppler shifts of each multipath component. Therefore, in order to guarantee a correct sampling of the multipath component and a correct correlation between consecutive samples, the Rayleigh independent variables are generated at least λ/8 meters and are filtered by a Doppler filter with a cut-off frequency equal to $B_d/2$ [5]. The Doppler filter suggests by [5] is a Butterworth filter, more realistic than a Jakes filter conventionally used.

Finally, since the direct signal component and the multipath component have to be added in order to generate the received signal, the direct signal component is generated at the same frequency than the multipath component, and its variations are then smooth by a Butterworth filter with a cut-off frequency significantly smaller than the overall channel generation frequency.

3-state model: Perez-Fontan model classifies the received signal into three states, according to the impact level of the propagation channel.

More specifically, each state corresponds to a particular environment configuration, representative to the strength of the shadowing/blockage effect on the received direct signal component. The first state corresponds to LOS visibility conditions, the second state to a moderate shadowing and the third state to a deep shadowing. Therefore, each state has associated a different set of Loo parameters for a fixed type of environment, a fixed satellite elevation angle and a fixed signal carrier band.

The state changes are very slow because they represent the transition between two different obstacles [3]. The state frame length l_{frame} corresponds to the average of the state length, in the order of 3-5 meters [4].

The state transitions are dictated by a first-order Markov chain [4], defined by the state transition probability matrix P (see Figure 2).

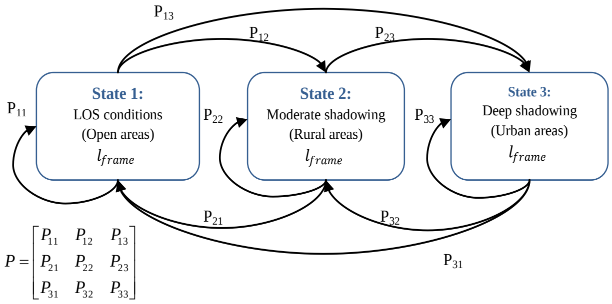

Figure 2: First-order Markov chain state transitions process

This model was referenced in the COST (European Cooperation in the field Of Scientific and Technical Research) in March 2002. Nevertheless, this model presents some limits.

<u>An Evolution of the Perez-Fontan model: the Prieto Model</u>

The Perez-Fontan 3-state model presents some limitations which involve a mismatch with reality. R. Prieto-Cerdeira proposes an evolution of the Perez-Fontan model, using it as a baseline. The same ensemble of measured data which was used by Perez-Fontan has been reanalysed, considering new assumptions:

- A classification in two states instead of three for the Perez Fontan model, and
- Loo parameters defined by random variables instead of constant values as for the Perez-Fontan model.

The mathematical model core is thus similar but two major differences appear.

2-state model: In the Prieto model, environmental conditions are classified in two states instead of the three of the Perez Fontan model:

- “Good” for LOS to moderate shadowing, and
- “Bad” for moderate to deep shadowing.

These two states represent two different macroscopic shadowing/blockage behaviour [5].

The state transitions are dictated by a semi-Markov model: the state changes are not anymore ruled by transition probabilities, we directly move from one state to the other (see Figure 3).

The duration of each state τ_{state} is defined by a statistical law. Reference [5] suggests that the duration of each state follows a Log-Normal distribution, whatever the state Good or Bad. The parameters of the Log-Normal distribution depend on the propagation environment. The database used in this paper to determine the Log-Normal parameters has been extracted from [5].

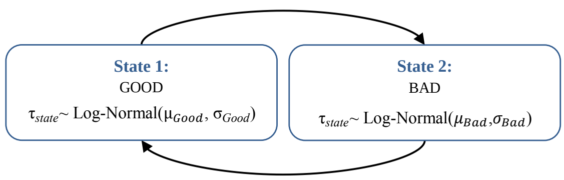

Figure 3: Semi-Markov chain state transitions process

The transitions between states have to be controlled in order to represent the reality as faithfully as possible, avoiding unrealistic jumps of the direct component amplitude. In this way, a maximum slope of 5 dB/m of the direct component is imposed [5].

Loo parameters generation: To compensate the reduction in the number of states (from three to two), both states of the Prieto model are allowed to take up a wide range of possible parameters values, compared to the Perez-Fontan model for which the parameters values were constant. The Loo parameters designated by (α_{db}, Ψ_{db}, MP_{db}) in the Perez Fontan model are noted as (M_A, Σ_A, MP) in the Prieto model [5]. They represent the same physical characteristic in dB but their numerical value is determined in a different way.

The new analysis led by Prieto on the same measurement campaigns as Perez Fontan, shows that the probability distribution which best fits the experimental trend of each one of the Loo parameters value, M_A, Σ_A and MP is Gaussian. Therefore, in order to determine the Loo parameters values associated to each new state, a new random number following a Gaussian distribution should be generated for each Loo parameter instead of determining always the same constant parameters value for a given state. Moreover, the Gaussian distribution for each Loo parameter is different, with its mean noted as μ and its standard deviation as σ. However, analyzed data demonstrates that the standard deviation of the direct signal component Σ_A and its mean M_A are dependent: M_A conditions Σ_A. In order to model this relationship, the Gaussian parameters (μ, σ) associated to Σ_A are determined through second degree polynomials evaluated at M_A. The determination of the Loo parameters are summarized in Table 1.The database used in this paper to determine μ_1, σ_1, a_1, a_2, a_3, μ_3 and σ_3 has been extracted from [5], according to the simulated environmental conditions:

- The type of environment (semi-urban, urban, deep urban…),
- The satellite elevation angle,
- The signal carrier band,
- The channel states.

Table 1: Loo parameters generation

M_A ~ Gaussian(μ_1, σ_1)	μ_1 is fixed, depending on environmental conditions
	σ_1 is fixed, depending on environmental conditions
Σ_A ~ Gaussian(μ_2, σ_2)	$\mu_2=a_1*M_A^2+a_2*M_A+a_3$ a_1, a_2, a_3 are fixed, depending on environmental conditions
	$\sigma_2=b_1*M_A^2+b_2*M_A+b_3$ b_1, b_2, b_3 are fixed, depending on environmental conditions
MP ~ Gaussian(μ_3, σ_3)	μ_3 is fixed, depending on environmental conditions
	σ_3 is fixed, depending on environmental conditions

The generation of the received signal complex envelope samples following a Loo distribution for the Prieto channel model is exactly the same as for the Perez-Fontan model (Figure 1). The only difference between the channel models is the Loo parameters value determination as it is illustrated in Figure 4.

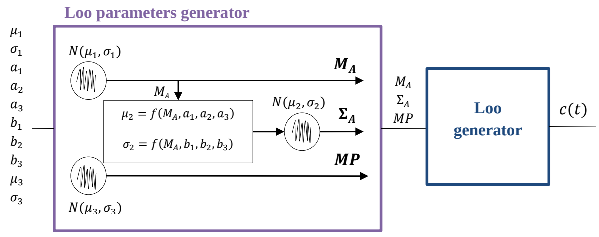

Figure 4: Generation of Loo samples for the Prieto channel model

However this model presents some limits. Firstly it is a narrowband model, which does not take into account the delay between the LOS signal and the echoes. And in addition, the databases used for the statistic distributions parameters values come from old measurement campaigns (low resolution, satellite azimuth angle missing).

3) Wideband Model

The propagation channel model described in this section is wideband, contrary to the previous propagation channel model (Prieto based on Perez-Fontan) which is narrowband. The difference lies in the multipath component modeling. On one hand, in the Prieto channel model, all the components are considered to be received at the same instant of time, the multipath echoes being added among them, resulting into a Rayleigh Distribution, and added to the LOS component as well. In this way, the time delay between the LOS and each multipath echo is not represented and the resulting received component follows a Loo distribution. On the other hand, in the DLR propagation channel model, the time delay between the LOS component and each multipath echo is modeled: each component is considered separately. Indeed, the DLR model targets satellite navigation systems and has been specially designed in order to study the multipath effect in GNSS receivers [8].

Therefore, the propagation channel impulse response provided by the DLR model [11] is represented by the sum of the LOS component and the different multipath echoes (5), each echo being associated with an amplitude, a phase and a time delay (delay between the LOS component and each echo).

$$h(t,\tau) = c_{direct}(t)\delta\big(\tau - \tau_{direct}(t)\big) + \sum_{l=1}^{L} c_l(t)\delta\big(\tau - \tau_l(t)\big) \quad (5)$$

Where:

- h is the propagation channel impulse response,

- c_{direct} is the direct signal component channel complex envelope,
- τ_{direct} is the propagation time,
- L is the number of echoes,
- c_l is the propagation channel complex envelope associated with the lth echo,
- τ_l is the delay between the direct signal component and the lth echo.

In order to provide the impulse response of the propagation channel, the DLR model generates an artificial scenario representing the characteristics of a given urban environment (see Figure 5) where a user can move, with potential obstacles to the received signal: buildings, trees, lampposts and reflectors. These obstacles are statistically generated but the attenuation, the phase and the delay associated to the LOS and multipath components are partly deterministically determined by ray tracing and geometric techniques. Furthermore, the number of echoes and their life span are statistical variables depending on the satellite elevation.

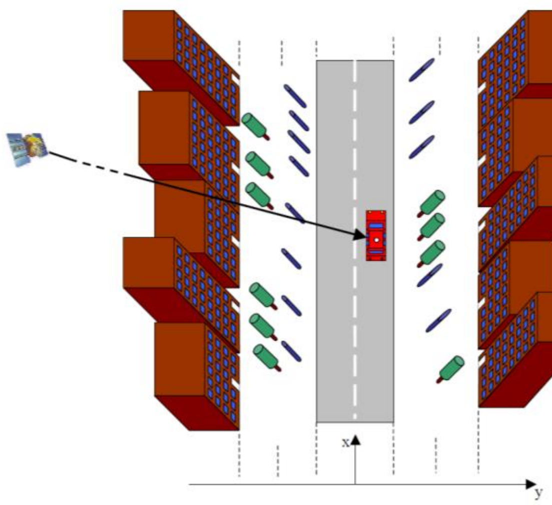

Figure 5: Scene example generated by the DLR propagation channel model [10]

The generation of this scenario, the characterization of its obstacles and, in summary, the design of a wideband model [6] being partly deterministic partly statistic, was possible thanks to a high delay resolution measurement campaign launched by the DLR in 2002 [9]. This model is freely accessible on the DLR website.

Finally, this model is the reference wideband model for the ITU (International Telecommunication Union). It is really realistic and seems to be the most appropriate in the navigation application case [12].

Nevertheless, the amount of data necessary to generate enough time series to do statistics with this model is important, as well as the time dedicated to the simulations.

II- Presentation of the simulation tool SiGMeP

The software simulation tool SiGMeP has been developed in order to be able to compute the demodulation performance of any GNSS signals in a realistic urban LMS channel model.

SiGMeP tool is a C language software organized as described in Figure 6 and Table 2. Current and future GNSS signals have been implemented in order to analyse their demodulation performance in open and urban areas, and to be able to compare them. Furthermore, these demodulation performance results could be used as a benchmark for new designed GNSS signals demodulation performance tests.

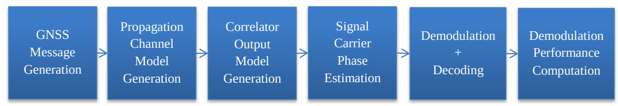

Figure 6: Simulation tool SiGMeP structure definition

Table 2: Simulation tool SiGMeP structure description

GNSS Signal Generation
➢ GPS L1C/A
➢ GPS L2C
➢ GPS L1C
➢ Galileo E1OS
Propagation Channel Modeling
➢ AWGN channel model
➢ Prieto channel model
➢ DLR channel model
Correlator Output Modeling
➢ Model based on partial correlations
Phase Tracking
➢ Ideal signal carrier phase estimation
➢ PLL tracking
Demodulation Performance Computation
➢ BER
➢ WER
➢ EER

As detailed in section I, two LMS propagation channel models have been developed in the simulation tool: the narrowband Prieto channel model and the wideband DLR channel model.

The received signal is modeled at the correlator output level. A classical correlator output model is used. However, the standard correlator output model is only valid when the variation of the incoming signal's parameters is limited. In particular, it is imposed to have a constant incoming carrier phase, or a linear variation of the incoming carrier phase with a locked PLL tracking. As a consequence, such assumption might not be valid over long periods for a received signal that went through an LMS channel. SiGMeP thus has the ability to use partial correlator output (see Figure 7), obtained when the above mentioned assumption on the phase variation is ensured, to build the true correlator output (since the correlation operation is linear, it is just the sum of the partial correlator outputs) at the desired rate (which can be different for tracking and data demodulation). In the present case, the partial correlator outputs are obtained at high sampling frequency equal to 0.05 ms.

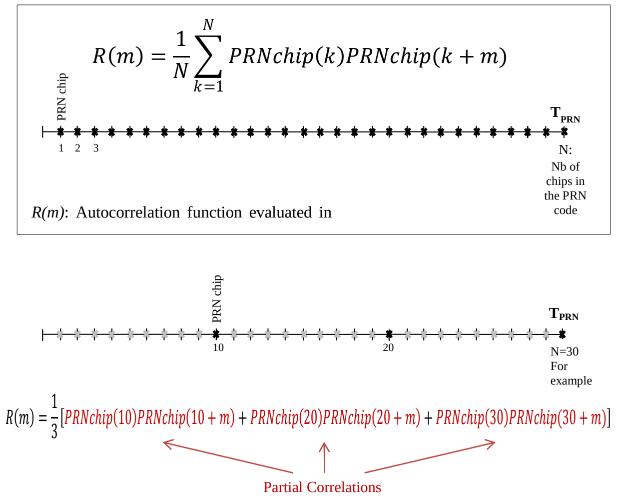

Figure 7 : Partial correlations illustration

The spreading code delay, between the received LOS signal component and the receiver spreading code locally generated, is assumed to be perfectly estimated (note that this assumption validates the generation of partial correlations explained before).

In a GNSS receiver, the received signal phase is estimated using a PLL. In order to investigate its impact on the demodulation performance, ideal phase estimation is compared with PLL tracking.

For the narrowband Prieto channel model, each received signal complex value corresponding to the sample k is multiplied by $e^{-j\,phase_{channel}(k)}$, which corresponds to the phase compensation by the channel model phase.

Whereas for the wideband DLR channel model, each received signal complex value corresponding to the sample k is multiplied by $e^{-j\,phase_{resulting}(k)}$, with:

$$phase_{resulting}(k) = phase\left\{\sum_{l=1}^{L} \frac{R(\tau_l(k))}{N} c_l(k)\right\} \quad (6)$$

Where:

- L is the number of taps for the kth sample,
- R is the autocorrelation function of the PRN code,
- τ_l is the delay between the direct signal component and the lth echo,
- N is the number of samples in *TI*,
- c_l is the propagation channel complex envelope associated with the lth echo.

Demodulation performance of GNSS signals in SiGMeP is studied through the Clock and Ephemeris Data (CED) Error Rate (CEDER): the only data required by the receiver to provide the user position being the CED.

III- Methodology for Providing GNSS Signals Demodulation Performance in Urban Environments

The ultimate goal of this work consists of testing GNSS signals demodulation performance in urban environments. Historically, the classical methodology used to provide the demodulation performance in the GNSS context consists in computing the CEDER as a function of the received C/N_0. However, we think that this method is not appropriate for dynamic channels and thus we propose a new approach in this section to compute GNSS signals demodulation performance in urban environments.

Contrary to the AWGN channel model case, the LMS urban channel model is a dynamic model. In a dynamic propagation channel, the received signal power is changing because of the user movements and the environmental variations. As a consequence, the received C/N_0 value fluctuates significantly during the exposure time. Therefore, it is no longer possible to determine the CEDER as a function of the received C/N_0 as it is made in the classical methodology.

For example, imagine that during one navigation message duration (equal to 18s for GPS L1C), the moving user passes in front of a building. The GNSS signal is shadowed or blocked by the building, which attenuates significantly the received signal power C at the receiver input. In this situation, the received C/N_0 value has changed during one message duration and thus during the time dedicated to compute the navigation message error probability (or CEDER). As a consequence, this error probability value does not correspond to one received C/N_0 value. Therefore, there is no operational meaning in representing the demodulation performance as a function of the received C/N_0 in an urban channel context.

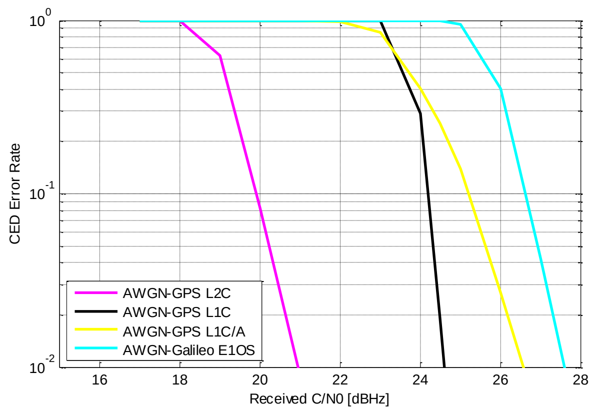

Figure 8: Demodulation performance of GNSS signals in the AWGN channel model with the classical methodology

However, for a given user platform and for a given satellite elevation angle, the theoretical received C/N_0

without any obstruction, that will be referred to as C_{LOS}/N_0, can be considered constant during the simulation time. It thus seems appropriate to represent the CEDER as a function of a constant C_{LOS}/N_0, the channel impact still being taken into account in the computation of the CEDER.

Therefore, we propose, as a first step, to represent the operational CEDER in an urban scenario as a function of the theoretical received C_{LOS}/N_0 (the value of C_{LOS}/N_0 considers thus no impact from the urban environment).

As a second step, for a given user platform, the C_{LOS}/N_0 values will be associated to one satellite elevation angle. Note that, in order to associate a C_{LOS}/N_0 value with a satellite elevation angle value, a refined link budget (taking into account the receiving platform) needs to be established, which will be done in further works.

To sum up, the first steps of the new methodology consisting in providing the CEDER as a function of the theoretical received C_{LOS}/N_0 (considering no channel impact) are presented in this article (section IV). The next steps consisting in providing the CEDER as a function of the satellite elevation angle will be presented in future works.

IV- GNSS Signals Demodulation Performance in Urban Environments

The demodulation performance of GPS L1C has been computed with the simulator SiGMeP by using the methodology described in section III. The CEDER is showed as a function of the theoretical C_{LOS}/N_0 considering no channel impact.

1) Simulated Conditions

The parameters used for the simulations presented in this article have been selected in order to be representative of difficult signal reception conditions. The signal reception conditions are listed in Table 3.

Table 3: LMS channel models parameters used for the simulations with SiGMeP

	Prieto	DLR
Sampling frequency	20 kHz	20 kHz
Environment type	Urban	Urban
User Speed	50 km/h	50 km/h
Band of the measurements	S-band	-
Satellite Elevation	40°	40°
Satellite Azimuth	Depending on the measurement campaign	0°, 45°, 90°

At the time of the article's publication, the simulations were conducted assuming a S-band signal since the L-band Prieto channel model parameters [5] seemed to not represent faithfully the real propagation channel.

The parameters used in the DLR model scene representation were determined to match the urban environment in the city center of Munich [16].

One of the limits of the Prieto model concerns the satellite azimuth. During the measurement campaigns used to design this model, the satellite azimuth was not recorded or no representative to a complete set with sufficient statistics.

The parameters of the PLL implemented for the non-ideal signal carrier phase estimation (representative to reality) are presented in Table 4.

Table 4: PLL parameters

PLL parameters	
Loop bandwidth	10 Hz
Integration time	1 symbol duration
Discriminator	Atan2
Loop order	3

Figure 9 shows 90 seconds of the Prieto channel model impact on the received signal amplitude and phase, generated with the parameters of Table 3.

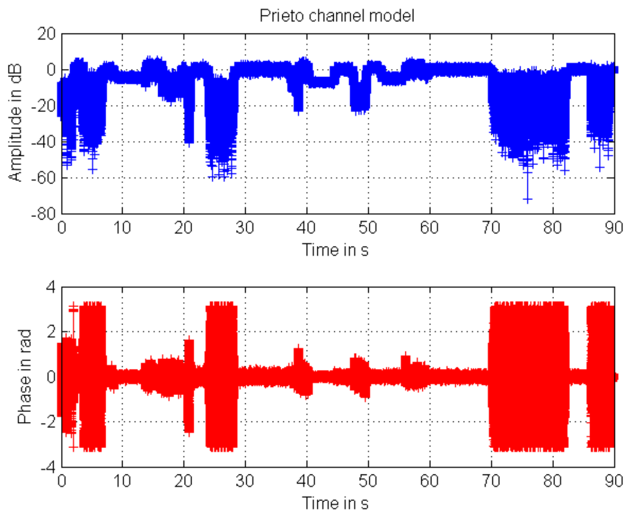

Figure 9: Received signal amplitude and phase with the Prieto channel model

Figure 10 to Figure 12 illustrate an example of the CIR generated by the DLR channel model for the simulated conditions defined in Table 3 and for satellite azimuth angles equal to 0°, 45° and 90°.

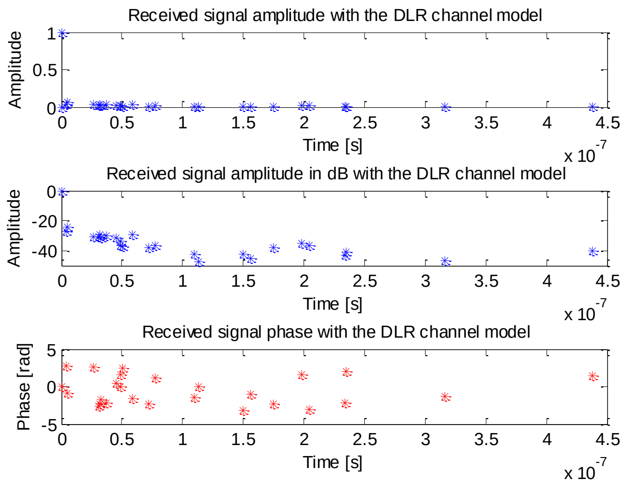

Figure 10: CIR example of the DLR channel model, with 0° of azimuth angle

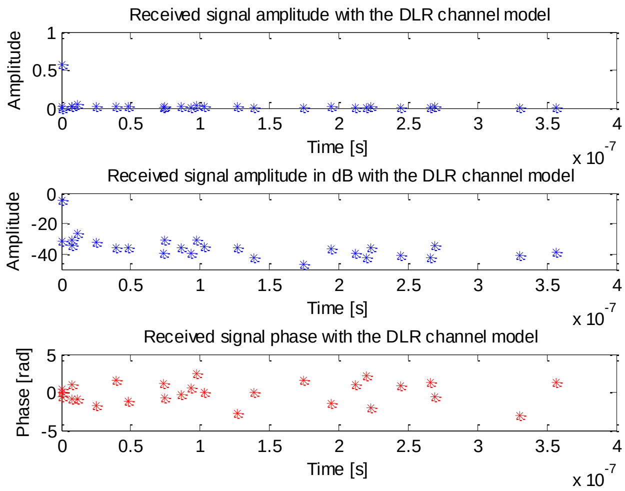

Figure 11: CIR example of the DLR channel model, with 45° of azimuth angle

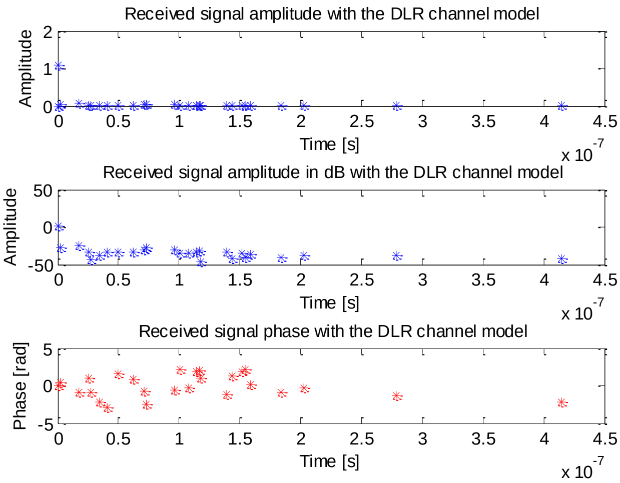

Figure 12: CIR example of the DLR channel model, with 90° of azimuth angle

Figure 13 to Figure 15 shows 90 seconds of the DLR channel model impact on the received LOS signal amplitude and phase, generated with the parameters of Table 3 (the multipath echoes impact is not represented in these figures).

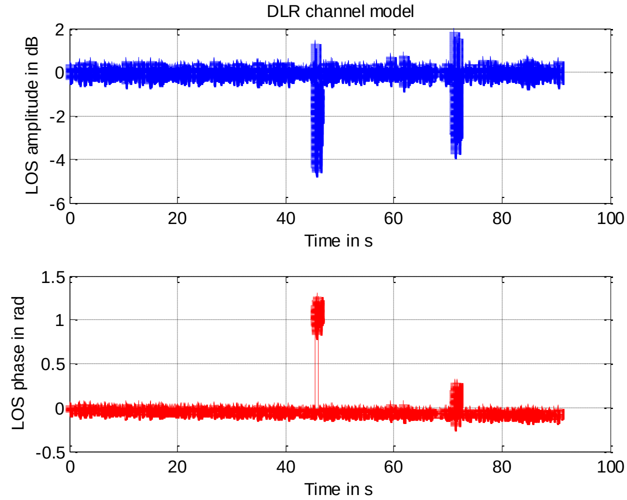

Figure 13: Received signal amplitude and phase with the DLR channel model, with 0° of azimuth angle

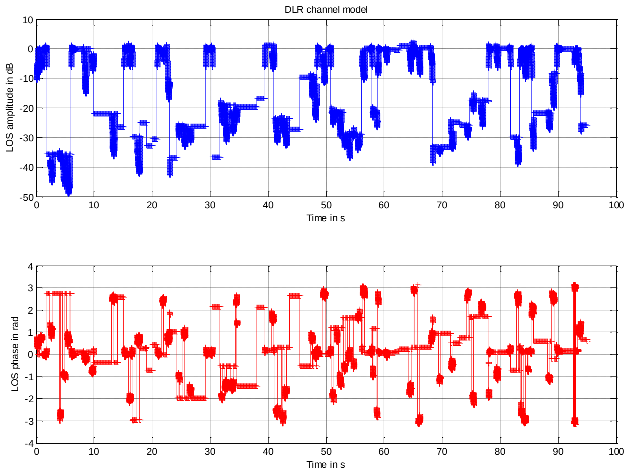

Figure 14: Received signal amplitude and phase with the DLR channel model, with 45° of azimuth angle

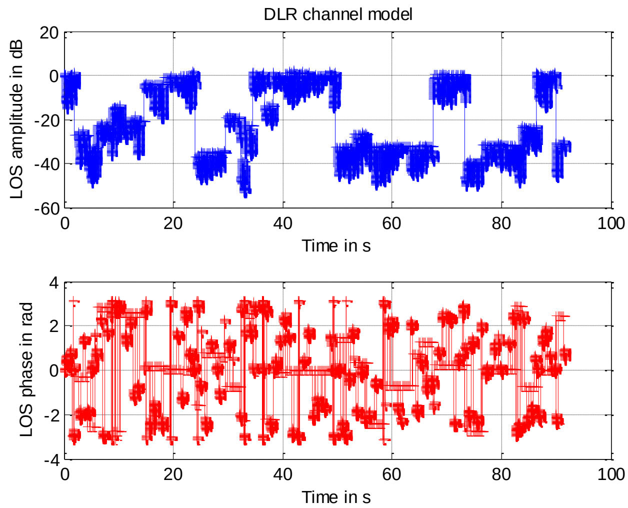

Figure 15: Received signal amplitude and phase with the DLR channel model, with 90° of azimuth angle

2) Classical Figure of Merit

The classical figure of merit represents the navigation message error probability (Bit Error Rate - BER, Word Error Rate - WER, CEDER) as a function of the received C/N_0 in open environments, or as a function of C_{LOS}/N_0 in urban environments (new methodology). The demodulation performance of GPS L1C is thus showed in this section by using the classical figure of merit with C_{LOS}/N_0 in the Prieto channel model and in the DLR channel model.

Prieto Model Results

Figure 16 represents the CEDER as a function of the theoretical received C_{LOS}/N_0 considering no channel impact, with ideal phase estimation and PLL tracking results obtained with our simulation tool SiGMeP for signal GPS L1C and with the Prieto channel model described in section I and the parameters listed in Table 3.

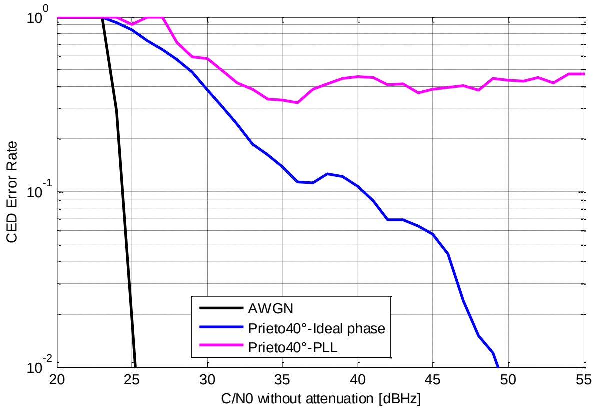

Figure 16: Demodulation performance of GPS L1C with the Prieto channel model

The demodulation performance with ideal phase estimation obtained for the Prieto propagation channel model is quite worse than the demodulation performance obtained for an AWGN channel as was expected. Moreover, the demodulation performance curve obtained with PLL tracking for the Prieto propagation channel model presents a floor. It seems to be caused by the received signal phase fluctuations generated by the Prieto channel model bad states, the PLL being not able to estimate the phase correctly, whatever the C_{LOS}/N_0 value.

DLR Model Results

Figure 17 represents the CEDER as a function of the theoretical received C_{LOS}/N_0 considering no channel impact, with ideal phase estimation obtained with our simulation tool SiGMeP for signal GPS L1C and with the DLR channel model described in section I and the parameters listed in Table 3.

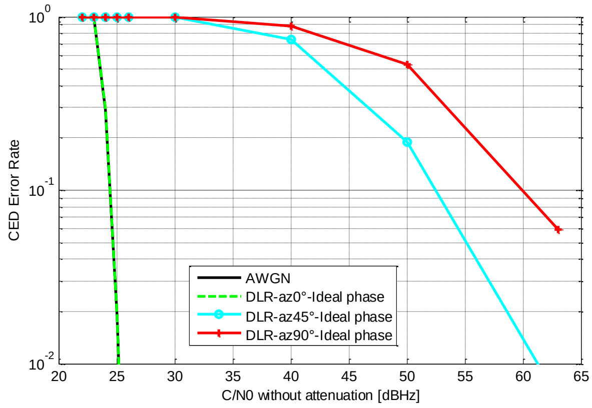

Figure 17: Demodulation performance of GPS L1C with the DLR channel model with 0°, 45° and 90° of azimuth angles

As it was expected, GPS L1C demodulation performance in the DLR channel model with ideal phase estimation is really different according to the satellite azimuth angle value. The results obtained with 0° of azimuth angle are similar than those obtained in the AWGN channel model, since in this configuration there are not obstacles between the satellite and the user. An azimuth angle equal to 90° is the worse configuration because of the buildings position.

Comparison between the Prieto and the DLR models

One of the purposes of this paper is to determine which one of these channel models Prieto or DLR, is the most appropriate in the navigation application case for the demodulation point of view (the final objective being to provide the performance of GNSS signals in urban environments).

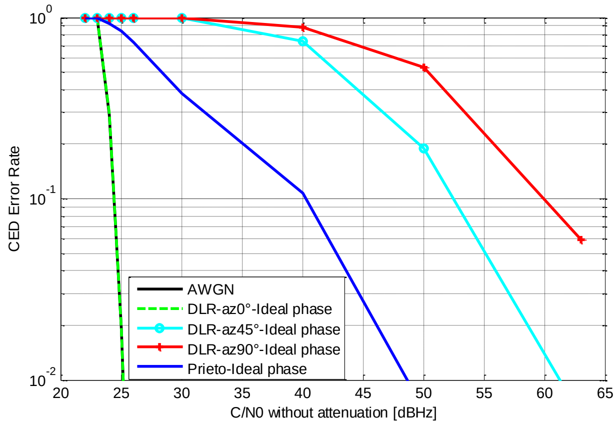

Figure 18: Demodulation performance of GPS L1C with the Prieto and the DLR channel models with an ideal phase estimation

However, it seems difficult to compare the results showed in Figure 17, because there are not representative of the same situation: the azimuth angle is fixed in the DLR channel model case whereas in the Prieto channel model case, it corresponds to a statistical mean of all the possible azimuth angles.

3) Refined Figure of Merit

In the context of this work which targets mass market applications, the maximum CEDER value eligible is 10^{-2}. In Figure 15, it seems that in the Prieto channel model, with ideal phase estimation, and simulated conditions defined in Table 3, the reference CEDER value is achieved for a minimum C_{LOS}/N_0 equal to 49 dB-Hz, which is very high. With a PLL tracking, it is not achievable. Through this classical figure of merit, it seems very difficult to be able to demodulate the navigation message in these conditions.

Therefore in this section, a refined figure of merit is proposed for representing GNSS signals demodulation performance in urban environments. It is provided in this paper for GPS L1C in the Prieto channel model.

The advanced figure of merit uses a specific GNSS system characteristic which leads to compute the navigation message error probability differently than for a classical communication system.

On one hand, in a GNSS system, once the GNSS receiver has succeeded in demodulating at least once the Clock and Ephemeris Data (CED) of the received GNSS signal and even if the navigation message cannot be demodulated again, the receiver can still determine its position for a while, as long as it is able to compute pseudorange measurements. The reason is that the CED remains unchanged during few hours, which means that the receiver does not need to demodulate the received navigation messages again during this period. Therefore, successfully consecutive navigation message demodulations are not necessary for the receiver to provide its position. On the other hand, for a classical communication system, the receiver must continuously demodulate the received signal.

To sum up, to compute the error probability of the demodulated CED for each received message to compute the GNSS signals performances does not seem to be adapted to GNSS systems: this classical approach provides a figure of merit representing the demodulation performance average of all the reception conditions whereas for a GNSS system only "good" conditions may be used. This statement is even more relevant in urban environments where the channel variations could be very damageable.

We propose thus a new way of representing the GNSS signals demodulation performance. First, a signal reception conditions configuration which provides a higher probability of demodulation success is searched. Second, the classical demodulation performance figure of merit is calculated for this configuration. Third and last, statistical results about time durations between these good signal reception conditions episodes are determined.

In this article, we have begun the investigation of this new approach in the Prieto channel model. A good signal reception condition has been studied: messages for which the channel state is "good" for their entire duration.

Table 5 and Figure 19 show the demodulation performance of GPS L1C with the Prieto channel model, through the new figure of merit described above.

Table 5: Statistical results about time durations between two messages entirely in good channel states

Parameters	40° of elevation	80° of elevation
Percentage of messages which are entirely in « Good » channel states	3,79 % ❖ 15 messages over 400 messages ❖ 4,5 min over 2h	19,7 % ❖ 79 messages over 400 messages ❖ 23,7 min over 2h
Mean duration between 2 messages entirely in « Good » channel states	❖ 25 messages ❖ 7,5 min	❖ 4 messages ❖ 1,2 min

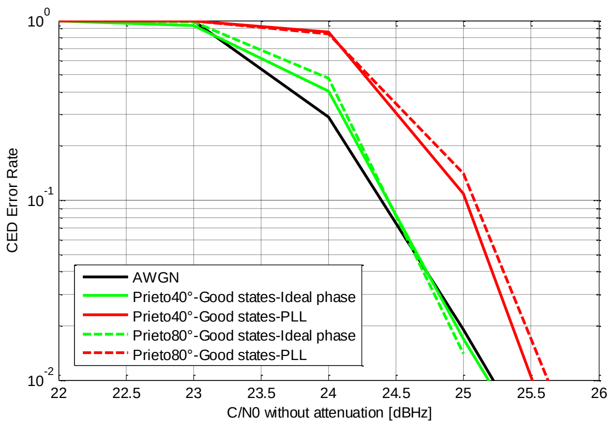

Figure 19: Demodulation performance of GPS L1C with the Prieto channel model forced to generate only good states

Table 5 shows that it is legitimate to use this good reception condition (force the Prieto channel model to generate only good states) for the demodulation performance computation of a GNSS signal since in 2 hours, which is the CED update time, there are 15 messages which are entirely in good channel states for 40° of elevation. It means that during each of these 15 messages, we have a probability of 10^{-2} to demodulate the CED without errors for a C/N_0 equal to 25.2 dB-Hz with an ideal phase estimation and 25.5 dB-Hz with a PLL tracking. With the classical figure of merit (see Figure 16), it showed that to be able to demodulate the CED with a probability of 10^{-2}, a C/N_0 equal to 49 dB-Hz was needed with ideal phase estimation and it seemed impossible when using a PLL for tracking.

V- Conclusions and perspectives

This paper has presented the SiGMeP simulation tool implementation, able to provide realistic GNSS signal demodulation performance in urban environments. Moreover, this paper provides the demodulation performance of GPS L1C using a narrowband model (Prieto) and a wideband model (DLR) with a new methodology: the CEDER is computed as a function of the theoretical received C_{LOS}/N_0 considering no channel impact instead of as a function of the received C/N_0, which is more adapted for urban environments. In addition, the demodulation performance in the Prieto channel model is represented through a new figure of merit: the CEDER is computed in good signal reception conditions and the time statistics of these good conditions are determined. A CEDER of 10^{-2} is achieved for a C_{LOS}/N_0 equal to 25.5 dB-Hz with a PLL tracking when the Prieto channel states are good during an entire message, which occurs on 15 messages over the 400 messages during when the receiver needs to demodulate at least once message to be able to compute the user position.

Finally, as future work it remains to deepen the new methodology which involves representing the demodulation performance as a function of the satellite elevation angle. In this way, a refined link budget needs to be established.

ACKNOWLEDGMENTS

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