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A MAP-MATCHING BASED APPROACH TO COMPUTE AND MODELIZE NLOS AND MULTIPATH ERRORS FOR GNSS POSITIONING IN HARD AREAS

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In Global Navigation Satellite systems (GNSS), the performances of classical localization methods show a significant degradation in constrained environments (urban and indoor environments), due to Non-Line-of-Sight(NLOS) and Multipath phenomena affecting GNSS signal. In order to improve positioning accuracy in hard environment, this paper aims to propose an approach to compute and adapt the NLOS and Multipath error model to GNSS signal reception conditions. The approach aims firstly to propose a Map-Matching based-technique to compute Multipath and NLOS errors in real time positioning, secondly, to test adequacy of these errors with the most used models in the literature and finally to model the Multipath and NLOS errors using Gaussian mixture noise. As a result, we have shown that a Gaussian, Rayleigh and Uniform model were not be able to model effectively Multipath and NLOS errors and we have demonstrated that a Gaussian mixture model can approximate these errors and improve positioning accuracy in urban environment.

Keywords: GNSS, Hard environment, Map-Matching, Masking, Multipath, NLOS.

1 Introduction

A Global Navigation Satellite System (GNSS) is the standard generic term for satellite navigation systems that provide autonomous geo-spatial positioning anytime and anywhere in the

world.
Since these systems are penetrated critical domains, i.e. maritime transport and civil aviation, requiring high accuracy, the performance criteria have been established to qualify these systems [1]; namely : accuracy, availability, continuity and integrity. However, despite the high precision required for positioning systems, the satellite positioning is affected by several problems related to signal propagation in the atmosphere (ionospheric and tropospheric errors), the instability of clocks, the orbital error, obstacles in receiving environment and receiver noise [2]. Therefore, the errors caused by these phenomena lead sometimes to significant errors.
Thus, most of the previously cited errors can be corrected by models, such as Klobuchar single-frequency model for ionospheric error [3]. However, the NLOS and multipath errors related to local phenomena remain not well modeled and are always the subject of studies in several laboratories around the world.
In the literature, we can find many types of techniques to enhance the localization performance in constrained environments, like Statistical filtering techniques, pseudoranges selection, 3D model of city and multi-sensor systems.
In this paper, to improve positioning accuracy in these environments, our research work aims to propose an approach to compute and model the NLOS and Multipath errors. In a simulation study, using real GNSS signal, we have proved that Gaussian, Rayleigh and Uniform model were not be able to model effectively multipath and NLOS errors. Simulation data were acquired in real environment (Toulouse, France).
The paper is organized as follows. In section II, an introduction of GNSS systems and urban positioning problem is presented. In section III, the related works are presented. The proposed approach to compute the NLOS and multipath errors is presented in section IV. The experimental study is presented in section V. In section VI, we have presented the impact of the proposed model in GNSS positioning. We have presented the proposed Multipath and NLOS Error Model for each signal reception state in section VII. The final section concludes this paper and discuses future work.

2 GNSS Systems : Overview

In this section, we cover the background of the GNSS systems architecture, the GNSS receiver functioning, the problem of positioning in urban canyons and the GNSS measurement model. Despite the study of GNSS systems functioning is not the main purpose of this paper, understanding their architecture and functioning is a necessary and important step for the realized work.

2.1 GNSS Systems Architecture

The Global navigation satellite systems share a common global architecture,consisting of three segments (cf. figure 1) [3] :

- Space Segment : Is formed by a satellite constellation.
- Control Segment : It monitors the satellite transmission, perform analyses, and send commands and data to the constellation. Each navigation satellite system has its own control segment composed of measurement and control stations.

- User Segment : This includes all receivers/processors and antennas which receive GNSS signals.

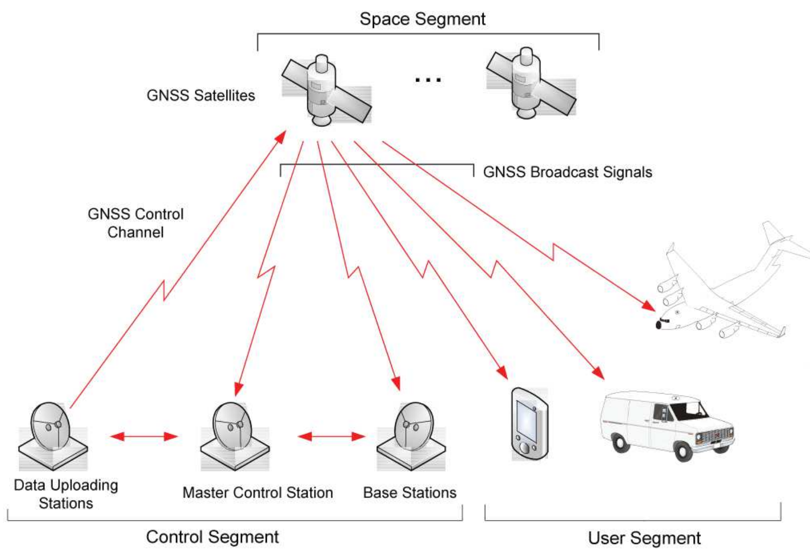


Fig. 1. GNSS Architecture [4].

2.2 GNSS Receiver Functioning

The main functions of the receiver is to capture signals transmitted by satellites in view and decode the navigation message in order to compute the transit time of the signal. The ranging codes broadcasted by satellites allows to GNSS receiver to measure the transit time of the signals and consequently to determine the range between satellite and user.

Thus, from the information provided by the navigation message, the user position coordinates and the user clock offset are computed using trilateration method [2]. Four satellites are normally required to be simultaneously "in view" for 3-D positioning purposes. Therefore, in order to compute the position of the receiving antenna, the receiver must perform the following operations [5] [6]:

- Acquisition : This operation consist to detect all satellites in view to the user. If a satellite is visible, the acquisition must determine the following two properties of the signal : Frequency and Code phase.
- Tracking : The main purpose of tracking is to refine the coarse values of code phase and frequency and to keep track of these as the signal properties change over time. This step contains two parts : code tracking and carrier frequency/phase tracking.
- Navigation Data Extraction : After a successful signals tracking, the navigation message was extracted from the received signal.
- PVT Computation : The final task of the receiver. It consists to compute the user position, velocity and time.

2.3 Urban Positioning Problem

The global navigation satellite systems suffers from many technical limitations for their use in highly degraded environments (urban environments and inside buildings) [7] [8] [9].
The reception of GNSS signals is disturbed by the surrounding environment of the antenna (vehicles, constructions, vegetation, etc). These disturbances can be due to three phenomena : masking, multipath and NLOS reception (cf. figure 2).

- Masking : One of the major problems using the navigation satellite systems in urban areas. Thus, they occur when the signal is blocked by various obstacles.
- Multipath : This phenomenon occurs when the signals incoming from satellites can undergo reflections by obstacles near the antenna (buildings, walls, vehicles, and the ground). The reflected signals can interfere with the directly received signals and take more time to reach the receiver than the direct signal.
- NLOS reception : This phenomenon occurs where the direct signal (LOS signal) is blocked and the signal is received only via reflection.

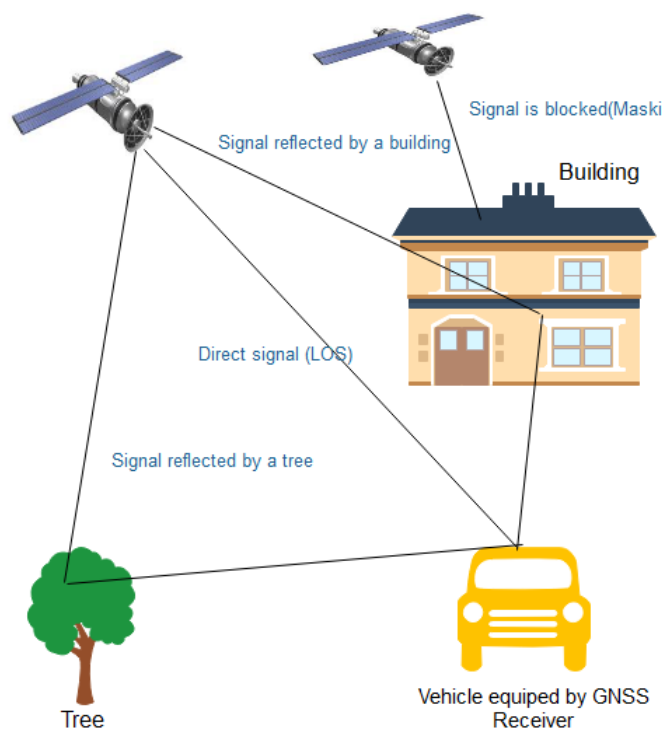


Fig. 2. Masking , Multipath and NLOS reception.

The multipath and NLOS phenomena disturb signal reception, notably, adding a delay to the propagation time. Consequently, such as the pseudorange measurements being deduced of time propagation, an additional error on pseudorange estimation will be added.

2.4 GNSS Measurement Model

The GNSS positioning is based on triangulation (or circular positioning) method (cf. figure 3) [2]: the distance between user and satellites is measured by multiplying the travel time by the speed of light and its expressed as functions of the satellites and user coordinates. Travel time is measured by comparing the time of emission (provided by the satellite) with the time of reception (measured by the receiver). The Satellite clocks can be synchronized with a global GNSS time using information contained in the navigation message broadcasted by satellites. However, the offset between user clock and GNSS time cannot be predicted and needs to be estimated at the same time as the position.

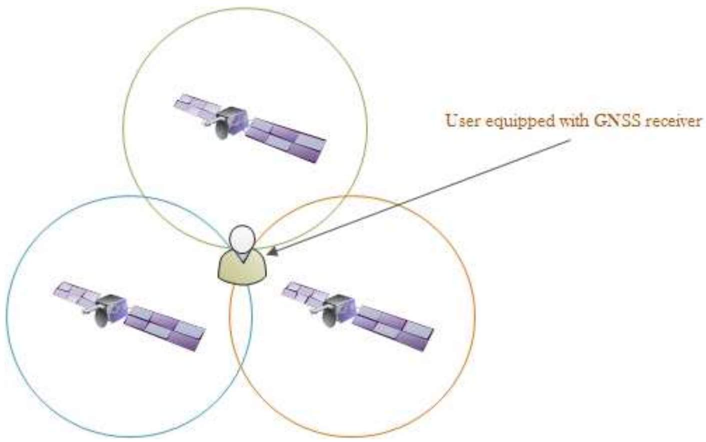


Fig. 3. Trilateration [10].

The GNSS measurement models that are effectively processed by the positioning algorithm are not ranges but pseudoranges, which have the following structure :

$$\rho_t^s = d_t^s - c(\delta t_u - \delta t_s) + I_t^s + T_t^s + eph_t^s + m_t^s + w_t \tag{1}$$

Where :

- d_t^s : The geometrical distance between the satellite and the user receiver. It equals :

$$d_t^s = \sqrt{(x_t - x_t^s)^2 + (y_t - y_t^s)^2 + (z_t - z_t^s)^2}$$

- (x_t, y_t, z_t) are the coordinates of the receiving antenna and (x_t^s, y_t^s, z_t^s) are the coordinates of satellite in the WGS84 standard.
- δt_s: The satellite clock offset.
- δt_u : The receiver clock offset.
- c : The speed of light.
- I_t^s : The Ionospheric error.
- T_t^s : The tropospheric error.

- eph_t^s : The orbital error.
- m_t^s : Error caused by signal reflections in constrained environment (NLOS or Multipath error).
- w_t : Receiver noise.

In equation 1, the variables x_t , y_t , z_t and δt_u are unknown and must be estimated by the receiver.

3 Related Work

In the literature, we find numerous studies treating the NLOS and multipath problem in urban areas, using a variety of approaches. In [11] and [12] a system have been proposed to improve GNSS performances by adding other sensors. However, it seems that these multisensors-based systems show a high system cost and complexity. With the development of ranging technologies, some work [13], [14] and [15] have used the 3D building information to estimate the multipath and NLOS effects.
In recent work, many involve models adaptation-based framework have been proposed. In [16], pseudorange errors are modeled by a Gaussian noise. However, other work have proved that a random Gaussian model become invalid in urban canyons [17] [10]. For a better estimation of NLOS and Multuipath error, in this paper, we have proposed a way to compute these errors in constrained environment and we have demonstrated that NLOS and Multipath errors can be modeled by a Gaussian Mixture distribution.

4 Proposed Approach to Compute NLOS and Multipath Errors

To estimate NLOS and Multipath errors m_t^s, our approach aims firstly to estimate the state vector X_t defined by equation 2 using a statistical filtering technique, such as Kalman filter or Particle filter. The schematization of a statistical filtering system is given by figure 4.

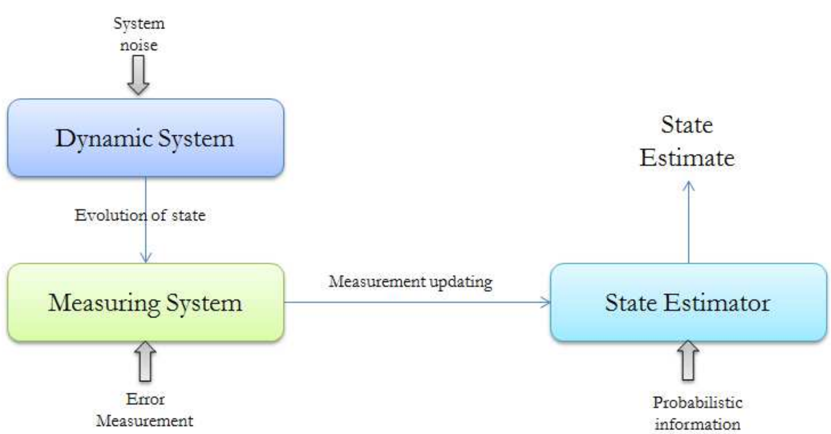


Fig. 4. A filtering system.

The state and observation systems are defined by :

$$X_t = f_t(X_{t-1}, V_t) \tag{2}$$

$$Z_t = h_t(X_t, W_t) \tag{3}$$

Where :
X_t : The hidden state vector.
Z_t : The vector of observations.
V_t : The noise of state vector.
W_t : The noise of observations.
f_t and h_t : The evolution functions of state and observations.
Secondly, we applied a real-time map-matching technique [18] [19] [20] [21] to re-estimate the previously estimated state vector X_t by statistical filter. A map-matching method consist to estimate a users position on a road segment. It take into account the estimated position by statistical filter and map data. In the most case, map-matching techniques give approximately the real position of user. For this, we have considered that the error of estimation given by a map-matching is negligible compared to NLOS or Multipath error.
Using the measurement model previously expressed (cf. equation 1), the pseudorange error is expressed as follows :

$$\varepsilon_t^s = m_t^s + w_t + \delta t_s + I_t^s + T_t^s + eph_t^s$$

We consider that $\delta t_s, I_t^s, eph_t^s$ and T_t^s are modeled and corrected, and the receiver noise w_t is a Gaussian white noise.
Our approach aims to compute the residues of pseudorange, which exhibit in our case the NLOS or multipath errors. This residue will be computed by subtracting pseudorange, real geometric distance, where user coordinates are estimated by map-matching technique, different errors affecting signal during its propagation and the receiver noise (cf. equation 4 illustrates the calculation of NLOS and Multipath error for satellite m at time t).

$$m_t^s = \rho_t^s - [d_t^s + c * \delta t_s + I_t^s + T_t^s + w_t + eph_t^s] + X(4) \tag{4}$$

Where :

- $\delta t_s, I_t^s, T_t^s, eph_t^s$ and w_t are already defined in equation 1.
- $d_t^s = \sqrt{(x_{t,map-matching} - x_t^s)^2 + (y_{t,map-matching} - y_t^s)^2 + (z_{t,map-matching} - z_t^s)^2}$ Where $(x_{t,map-matching}, y_{t,map-matching}, z_{t,map-matching})$is the predicted position using a robust map-matching technique.
- ρ_t^s : Is the pseudorange measurement obtained by multiplying signal travel time by the speed of light.
- $X(4)$: Is the fourth element of state vector, which equals to $c * \delta t_u$.

5 Experimental Study

In this section, in order to search the statistical model of Multipath and NLOS errors estimated by our proposed approach, we are tested the adequacy of these errors with the most model used in literature; namely, Normal, Rayleigh and Uniform model and we have applied some statistical test to search the adequate model.
For all presented results, We used a real GPS data. For this, a field data collection campaign

was carried out at Toulouse, France. The test scenario was selected so that the test vehicle followed a trajectory over a period of 1000 seconds. Figure 5 shows the reconstructed trajectory based on the GPS measurement performed by a professional receiver. The objective of the work is to asses the presence of obstacles generating Multipath reflections. The simulation environment is representative of various conditions that my appear in urban scenarios. We acquired the experimental data with a low-end receiver that shows very important pseudorange errors, since no smoothing on measure is performed and no processing to filter received signals is applied. This receiver allows as to have the raw measurements required for positioning in the output files, such as satellite positions, pseudorange measurements, Doppler measurements,etc. The data is computed out in collaboration with ISAE/SUPAERO University of Toulouse.

In order to test adequacy of multipath errors with the most model used in literature; namely,

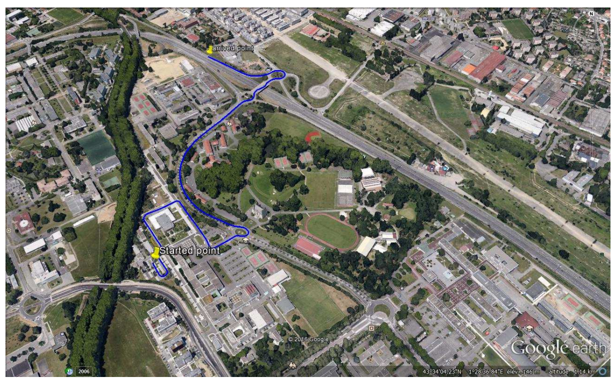


Fig. 5. Reference trajectory

Normal, Rayleigh and Uniform model, we have computed multipath and NLOS errors (using equation 4) for one satellite (PRN 5) for intervals time experienced a bad availability of C/N0. We note, when the multipath phenomenon occurs, we acknowledge a loss of power in the received signal that affects the C/N0(Carrier-to-noise ratio). Besides, in GNSS domain, a signal of good quality has a C/N0 on (C/A) code, at least of 38-40 dB-Hz [22]. In our computation, and to select only the attenuated signals, we have used the signals received with a value of C/N0 less than 40 dB-Hz.

- Normal Law : In probability theory, the normal (or Gaussian) distribution is a very common continuous probability distribution. It often used in the natural and social sciences to represent real-valued random variables whose distributions are not known. In GNSS domain, the observation noise is assumed to follow a Gaussian white model when we do not take account of the modeling of Multipath errors in constrained environment.

- Rayleigh Law : This law is generally used to describe the noise output of a telecommunications transmission chain. It often model the signals delay. For the navigation satellite systems, the signal delays cause errors for estimate the propagation time, so, more noisy pseudorange measurements.

- Uniform Law : In probability theory, the continuous uniform distribution is a family of symmetric probability distributions such that for each member of the family, all intervals of the same length on the distributions support are equally probable. We chose to study this law because in a few seconds interval time, we can consider that the conditions of localization remain almost the same.

In order to test the adequacy of these laws with the values of NLOS or Multipath errors that we have computed, we have applied a visual comparison, using Quantile-Quantile diagram (Q-Q plot), that will allow to evaluate relevance of adjustment between data and a probability distribution.
Figure 6 presents the results of comparison between the Multipath or NLOS errors and the different distributions cited above, using the Q-Q plot diagram. In general, the adequacy between tested data and theoretical distribution will be based on the linearity of graph. A dotted line is used as a reference line, which represents the obtained result if data was perfectly adequate with the theoretical distribution.
From figure 6, the result of comparison between the distribution of Multipath/NLOS errors and the Normal, Rayleigh and Uniform Laws (cf. figures 6a, 6b and 6c respectively) shows that the NLOS and Multipath errors data are clearly away from the reference line. Therefore, even if the Q-Q plot allows to have only a subjective judgment, some aspects and similarities between distributions may be determined. We can conclude that a Gaussian, Rayleigh and uniform model were not be able to model effectively Multipath and NLOS errors.
To search the statistical distribution of these errors, we are presented our Multipath/NLOS errors data by the histogram. From figure 7, we denote that the Multipath errors distribution is much more complex and multimodal. Consequently, we can assume that the Multipath and NLOS errors can be approximated by a finite Gaussian mixture model. In order to validate our assumption, we are tested our Multipath and NLOS data with the gaussian mixture distribution using Q-Q plot diagram. From figure 8, we show that the Gaussian distribution model perfectly the NLOS and Multipath errors.

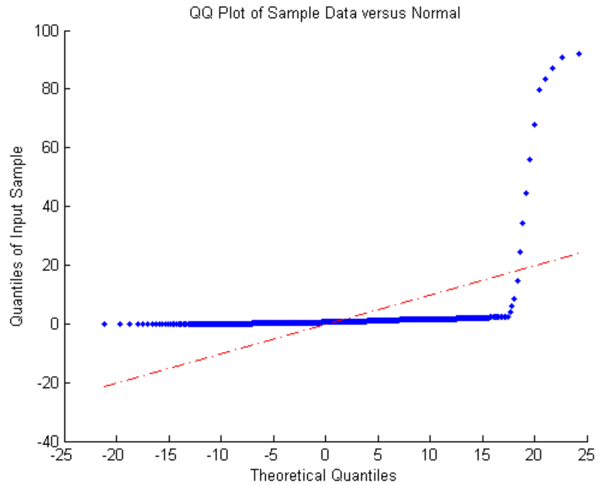
6 Impact on Positioning Accuracy

To prove that Gaussian mixture model can approximate the Multipath errors and improve positioning accuracy in urban canyon, we have shown the positioning errors using a random Gaussian mixture noise for estimating our Multipath and NLOS error in GNSS measurement model. From figure 9 we denote a positioning mean error equals to 14.4079 m using Gaussian white noise and equals to 6.2374 m using a Gaussian mixture noise. We can conclude that a Gaussian mixture model can improve positioning results in terms of accuracy.

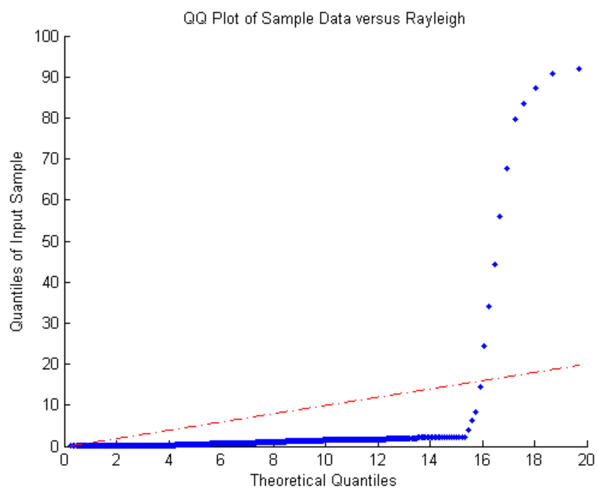
7 The Proposed Multipath and NLOS Error Model for each Signal Reception State

In constrained environments, according to the user position, obstacles close to the user and satellites position, the satellite signal can be received with or without reflexion. The errors m_t^s constructed by these propagation phenomena will have different statistical model according to each signal reception state. We assume three state of reception.

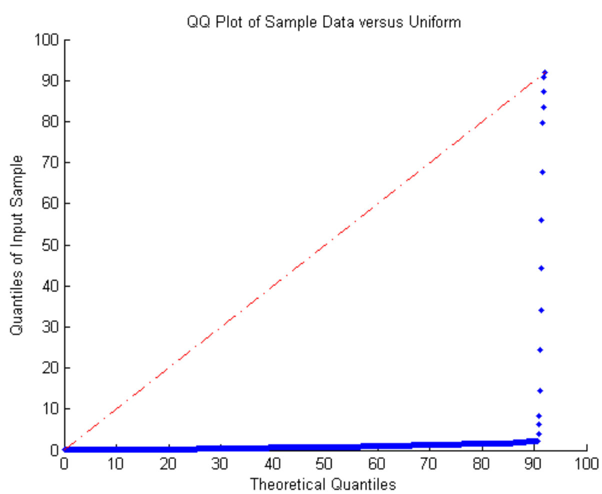
A) Direct reception (LOS):



(a) Q-Q plot of NLOS and Multipath errors data versus Normal



(b) Q-Q plot of NLOS and Multipath errors data versus Rayleigh



(c) Q-Q plot of NLOS and Multipath errors data versus Uniform

Fig. 6. Q-Q plot of NLOS and Multipath errors data versus Normal, Rayleigh and Uniform distributions

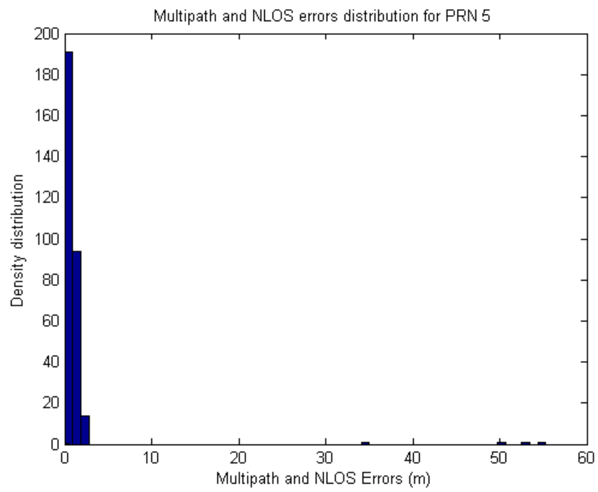


Fig. 7. Multipath and NLOS errors distribution for satellite PRN 5

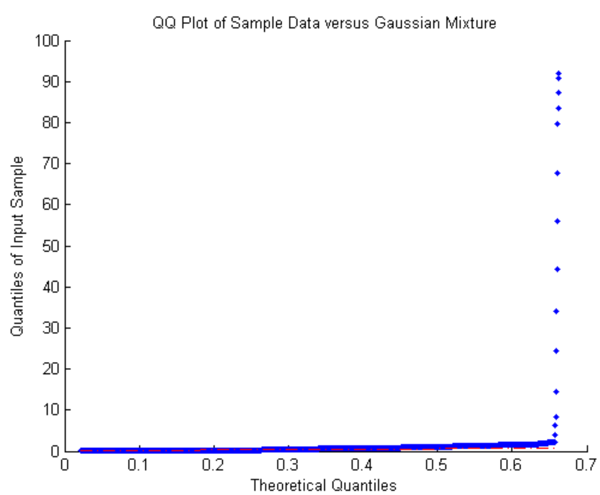


Fig. 8. Q-Q plot of NLOS and Multipath errors data versus Gaussian Mixture distribution

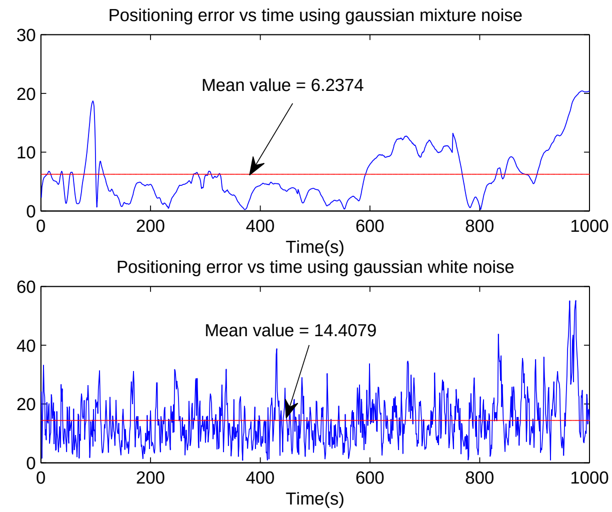


Fig. 9. Difference between theoretical and estimated 2D positions (m)

In this case, the satellite signal is received without reflexion, consequently, the pseudo-range is correctly estimated and m_t^s is null.

B) Multipath and NLOS reception: The satellite signal is received after reflexion on obstacles, Then, in this case m_t^s is not null and cannot be modeled by a Gaussian noise. We assume to model these error by a Gaussian Mixture noise.

$$m_t^s \sim \sum_{k=1}^{J} \pi_k N(x|\mu_k, \sigma_k^2)$$

Where :

- J : The number of component in the mixture.
- $N(x|\mu_k, \sigma_k)$: Is a Gaussian density, called a component of the mixture and has its own mean μ_k and variance σ_k^2.
- π_k : Mixing coefficients, which verify

$$\sum_{k=0}^{J} \pi_k = 1$$

.

C) Blocked reception: In this case, signal is blocked by the obstacles near to the receiver.

8 Conclusion and Future work

In this paper, we gave a general presentation about GNSS systems and the major problems which disrupt positioning in urban areas.

Our work was focused firstly to propose a technique to compute multipath and NLOS errors

in real time positioning, secondly, to test adequacy of multipath and NLOS errors with the most models used in the literature. As a result, we have shown that a Gaussian, Rayleigh and Uniform model were not be able to model effectively these errors. Finally, we have shown that these errors can be modeled by a Gaussian Mixture distribution.
Our future work will be focused to apply more robust statistical tests to validate the assumption that Multipath and NLOS errors follows a Gaussian mixture distribution and to use the Expectation Maximization (EM) algorithm for estimating the Gaussian Mixture parameters from data.

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