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# How to improve GNSS positioning Quality of Service for demanding ITS in city environments by using 3D digital maps

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## Abstract

The paper presents two different methods, so-called *light* and *heavy*, for taking into account the knowledge of the 3D environment of a vehicle in a city, where propagation phenomena can cause severe errors in positioning computation. The two methods make use of digital maps, but in a different way. The paper presents in details the methods compare their results in terms of hidden satellites detection and applies the light method on a real test site in Nantes to demonstrate the gain in terms of accuracy of the final position.

**Keywords:** GNSS positioning, quality of service, accuracy, integrity, multipath, non-line-of-sight signals

## Introduction

GNSS systems have significant potential in the development of Intelligent Transport Systems and associated services. Nevertheless, a major technical issue with respect to safety-critical and liability-critical applications (urban tolling for instance) is the quality of service not only in terms of accuracy, continuity and availability, but also integrity, which is the level of trust in the positioning solution. In strongly constrained environments, like city centres, the propagation phenomena in the surrounding of the antenna, more precisely diffraction and multipath, are responsible for severe errors on the raw observables (pseudo-ranges and Doppler measurements) that are measured by the receivers [1]. The most severe deviations (up to several tens of metres) may occur in case the reflected path is the only tracked, whereas the direct one is blocked. Such signals are called “Non-Line-Of-Sight” (NLOS) signals. In this context, the standard method of computing a position and the associated protection level coming from the civil aviation community [2] is no longer adapted.

A standard low-cost receiver, with no particular knowledge of the environment, acts blindly

when computing the navigation solution (Position, Velocity and Time) from the raw observables. Since it gives greater place to continuity and availability compared to accuracy, it will use most of the measurements even if the latter are strongly corrupted by propagation phenomena. When some a priori knowledge of the environment is embedded in the receiver, for instance under the form of a digital map with building height information, the strategy of the navigation solution can be significantly improved because the reception conditions of each signal can be characterized.

### **State of the art on Quality of Service improvement methods**

Traditional methods for improving Quality of Service of GNSS receivers, and particularly their Integrity, which has been developed in the civil aviation context, are based upon 2 different and complementary approaches:

- SBAS (Satellite-Based Augmentation Systems) approach, of EGNOS type, where all the signals covering a given zone are permanently monitored, in order to detect any abnormal behaviour and to update the error models at the raw measurements level [2],
- FDE (Fault Detection and Exclusion) method (also called RAIM), autonomous and based on only SW, consisting in detecting strongly biased pseudo ranges, thanks to a statistical test based upon redundancy of the satellites [4].

These two approaches are unfortunately almost inefficient in terrestrial urban environments where the assumptions supporting them are most of the time not satisfied.

For a few years, in addition to navigation process improvements, researchers have addressed the use of 3D models of the environment to analyse reception conditions and mitigate multipath phenomena, using generally image (real or virtual) processing techniques [6] [7].

### **Why using *a priori* knowledge of the environment to characterize reception conditions ?**

By combining the knowledge of the surrounding obstacles with advanced signal processing, the characterization of the observables quality can be significantly improved and consequently the quality of the computed position.

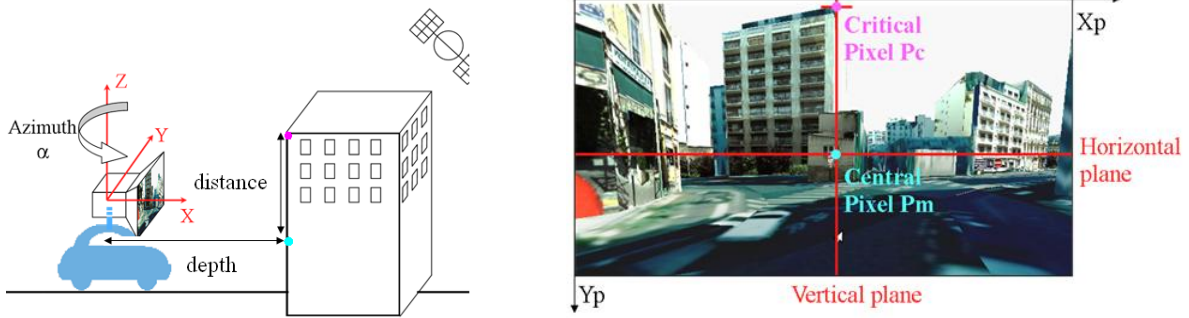
This 3D map usage described in this paper, at the Navigation Solution level, is not the only one that is of interest for improving the global process. The map data can also be used at the application level and at the DSP level. At the application level, the map information can be used to improve the direct estimation from the raw observables of the map-matched position, for instance in a particle filtering scheme in which the particles off the road are eliminated to constraint the solution [8] [9]. At the DSP level, the idea of exploiting 3D map data to support the tracking loops and to characterize the raw observables is a promising novel idea, which is under investigation at the moment. This paper will address only the way 3D map data can

improve the PVT computation, thanks to observable filtering and characterization.

### The “heavy method” based on a complete 3D model inside a GIS

This method, developed in the frame of the French CityVIP project, has already introduced in [3]. It is based upon the use of an embedded dedicated GIS developed by the French SME BeNomad and containing accurate 3D digital data of the environment from the French IGN (*Institut Géographique National*). Tests presented further in this paper were carried out in Nantes, where the 3D model accuracy is around 1 m.

The Software Development Kit (SDK) of the GIS makes map rendering like a virtual camera from which we control perfectly the intrinsic and extrinsic parameters would do (see Figure 1). It also offers the basic measurement functions of distance and depth from the produced image. Hence, a virtual image is made from the current GPS antenna location and for every satellite azimuth. Roll or pitch angles are set to zero. The focal distance is adjusted so that the top of the frontal buildings matches the height of the image.



**Figure 1: A virtual image and its 2 pixels of interest**

The critical elevation angle imposed by the environment is then determined: the algorithm determines the coordinates  $(X_{Pc}, Y_{Pc})$  of the critical pixel situated on the border between sky and frontal buildings. Knowing the coordinates of this critical pixel, and using the distance and depth measurement functions, we obtain:

$$\beta_c = \text{atan}\left(\frac{\text{getdist}(PC, PM)}{\text{getdepth}(PM)}\right) \quad (1)$$

Finally, we compare the critical elevation angle to the actual elevation angle of the satellite to decide if it has to be considered NLOS or not.

### The “light method” based upon a global classification of the streets inside a 2D map

#### *Classification of the urban environment*

The first step of the method consists in a classification of the urban environment. All the

circuit travelled by the vehicle is divided into homogenous sections having approximately the following constant geometric features: **width of the street** and **height of the buildings**. In order to refine this classification, we also take into account the **lateral position** of the receiver in the street. This indicator is normalized and takes the value “zero” for the extreme left side of the street and the value “one” for the extreme right side. Finally, each section of the street is identified by a unique class of urban configuration, defined by the triplet of parameters ( $H$ =Height of buildings,  $W$ =Width of the street,  $P$ =Position of the vehicle).

These classification data are included into the navigation database produced by our test facility, already containing satellite data and reference data, in order to affect to each satellite, at each time, the urban configuration surrounding the receiver antenna.

*The “mask of visibility”*

The second step of the method is based upon the hypothesis that in an urban constrained environment, the vision space above the vehicle is limited by the buildings. In this approach, the street is modeled by a fixed object, such as “shoes box” defined by the triplet of parameters ( $H, W, P$ ), in which the satellite receiver is in the center. From this model, the "mask of visibility" algorithm discriminates the satellites in LOS (Line-Of-Sight) from the satellites in NLOS (Non-Line-Of-Sight).

This detection depends on the following parameters:

- $el_b$  defines the critical elevation angle of the buildings imposed by the urban configuration, it is computed according to the triplet of parameters ( $H, W, P$ );
- $\beta$  represents the difference between the considered satellite azimuth and the orientation of the street, its value determines if the satellite above the street is in the left side or in the right side.

We summarize this algorithm for the two possible cases in the following table:

<i>Satellites on the left side of the street</i>	<i>Satellites on the right side of the street</i>
$-\pi \leq \beta \leq 0$ or $\pi \leq \beta \leq 2\pi$	$-2\pi \leq \beta \leq -\pi$ or $0 \leq \beta \leq \pi$
$el_b = \arctg \left  \frac{H}{P.W} \sin \beta \right $	$el_b = \arctg \left  \frac{H}{1-P} \frac{1}{W} \sin \beta \right $

**Table 1: Definition of the critical elevation angle**

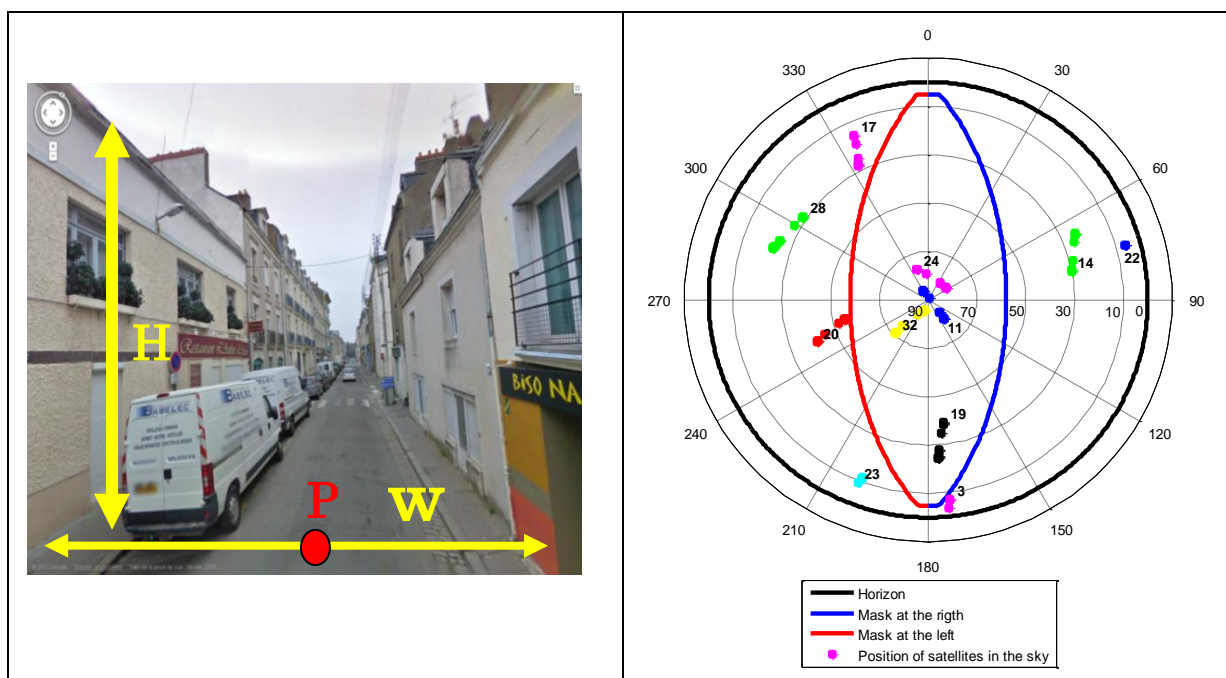
Finally, the condition of visibility by a receiver is given according to the value taken by the satellite elevation: if the satellite elevation angle is lower than the elevation of the buildings, then the satellite is in NLOS (outside the “mask of visibility”), otherwise it is in LOS (inside the “mask of visibility”). A result obtained by such a method is given on the sky plot of Figure 2.

*Application of the “light method” on a Nantes street*

We apply here this method on a street (*Les Olivettes* street) extracted from a measurement campaign carried out in March 2011 for the CityVIP project, in Nantes City centre, whose urban configuration was:  $H = 8$  m,  $W = 10$  m,  $P = 0.5$  (narrow street, small buildings).

The data of this campaign have been obtained by the test vehicle VERT from Ifsttar, equipped with its *Mobile Reference Trajectometer (MRT)*, to acquire the reference trajectory, often called “ground truth”. From each point of the reference trajectory, we can compute the “true distance” between antenna and satellite, for each tracked signal, and therefore the “true error” committed by the receiver. The GNSS receiver is a ublox LEA-4T.

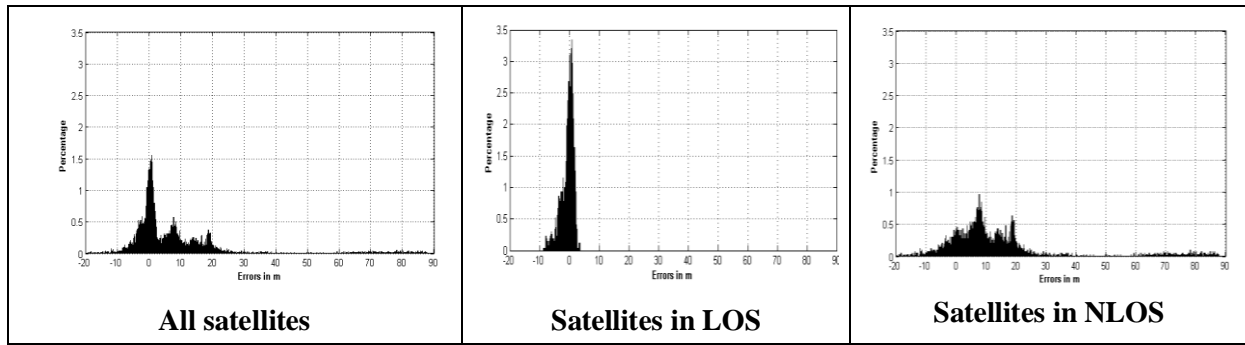
The application of the “mask of visibility” algorithm, illustrated in the Figure 2, provides as statistical results: 47.6% of satellites in LOS (satellites n°11, 19, 24 and 32) and 52.4% of satellites in NLOS (satellites n°3, 14, 17, 20, 22, 23 and 28).



**Figure 2: Illustration of the application of the “light method” on a Nantes street**

In order to validate this detection, from the pseudo ranges errors computed thanks to the reference trajectory, we draw the histograms representing the probability distribution law of the errors, respectively for the 3 cases: all satellites, satellites classified in LOS and satellites classified in NLOS. The distributions are presented in Figure 3.

The distribution law of the LOS satellites is centered at zero. The distribution law of the NLOS satellites is more extended and shows multipath effects caused by the urban constraints. It proves that all NLOS satellites are well detected and will be excluded for the positioning calculation. These distributions confirm the robustness of the method.



**Figure 3: Probability distribution laws of the pseudo range errors in street *Les Olivettes***

**Comparison of the 2 methods in terms of NLOS detection**

Both methods make LOS/NLOS decisions based on different 3D models and different assumptions on the vehicle (i.e. the GPS antenna) position. This section will compare these decisions, on the same test site (rue des Olivettes) as the one used in the previous section. 7527 satellites observations were aggregated in the following statistics (see Table 3) which represent almost 4 minutes at 4 Hz, with 4 different passes in this street during half an hour.

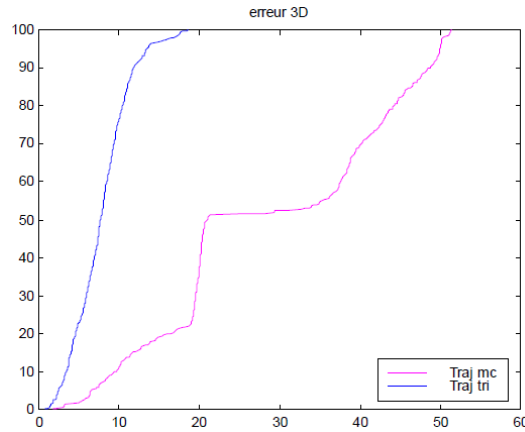
	LOS by the “light method”	NLOS by the “light method”
LOS by the “heavy method”	3582 svcs data (i.e. 47.6%)	304 svcs data (i.e. 4.0%)
NLOS by the “heavy method”	2 svcs data (i.e. 0.0%)	3639 svcs data (i.e. 48.3%)

**Table 2: Confusion matrix between the 2 methods**

With only a few percent of disagreement, both methods are remarkably consistent in the street considered, which demonstrates the relevance of the 3D model approximation suggested with the visibility mask approach.

**Results of the “light method” in terms of accuracy improvement**

In this section, we present some results concerning the exploitation of the characterization of reception conditions for the calculation of the position of the receiver, obtained with the basic method of least mean squares on the four passages of the section of the street *Les Olivettes*. At first, the positioning is computed by using all the available satellites tracked by the receiver, as it is done traditionally, in a second step, only with LOS satellites detected by the method. To assess the improvement of the position estimate achieved with this method, we present on Figure 4 the cumulative distribution function of the positioning error in 3D for all the satellites and for only the LOS satellites (pink: with all the satellites, blue: with LOS only).



**Figure 4: 3D accuracy improvement by excluding the NLOS satellites**

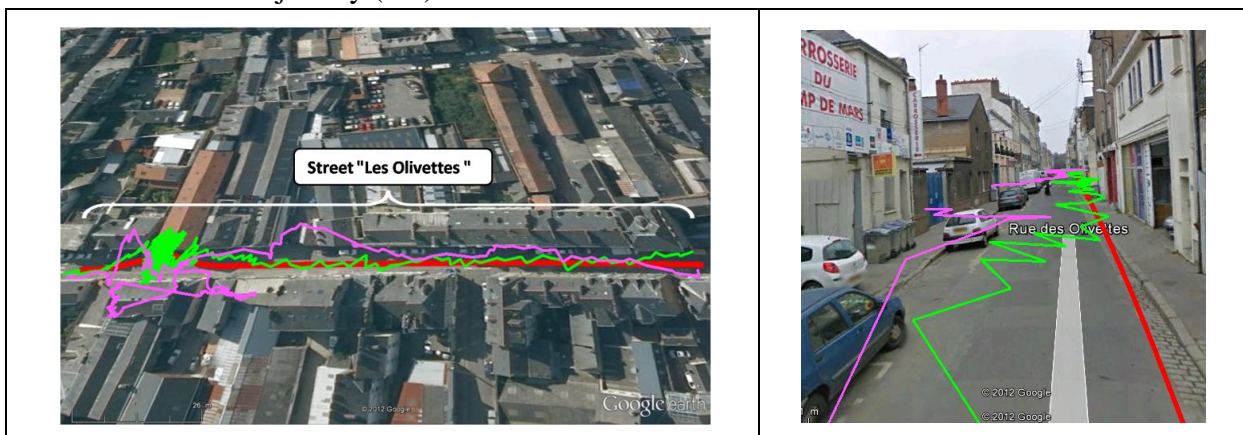
From these cumulative distribution functions of the positioning error in 3D, we focus in Table 3 on the results corresponding to the 5<sup>th</sup>, the 50<sup>th</sup> and the 95<sup>th</sup> percentile and the percentage improvement.

	5 <sup>th</sup> percentiles (m)	50 <sup>th</sup> percentile (m)	95 <sup>th</sup> percentile (m)
<b>All satellites :</b>	5.7	19.6	49.1
<b>Only LOS</b>	3.1	9.2	15.5
<b>Correction rate</b>	-46 %	-53 %	-68 %

**Table 3: Results of the positioning calculation error in 3D**

For example, if we take into account all satellites, 95 % of the positioning calculations have an error in 3D less than 49.12 m. With the LOS satellites only, this error in 3D is lowered to 15.51 m. To illustrate these results, we present in the picture below the trajectories computed for the fourth passage performed in the street. The figure below supplies the following information:

- the trajectory calculated with all the satellites (pink);
- the trajectory calculated with satellites in LOS only (green);
- the reference trajectory (red).



**Figure 5: Illustration of the positioning error in the section of street *Les Olivettes***



## Conclusion and perspectives

We present in the paper two different methods for characterizing the reception conditions and the pseudo ranges quality for each satellite tracked by the receiver: a “heavy” one based upon a full 3D model and a “light” one based upon the classification of all the travelled streets in terms of visibility. A statistical comparison of the two methods on their capacity to discriminate LOS/NLOS satellites shows very similar results.

About position accuracy, a comparison between the solution obtained by a simple Least Mean Squares method applied with all the tracked satellites and applied with only the satellites detected as LOS shows significant improvements of the order of 50 % in terms of 3D errors.

In the next future, this promising method, based upon the mask of visibility, will be applied to a much larger sample of data, obtained in Paris and Toulouse, to validate these first results.

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