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How to enhance accuracy and integrity of satellite positioning for mobility pricing in cities: the Urban Trench method

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Abstract

Mobility pricing based on GNSS is bound to become a significant tool for both traffic control and infrastructure funding, compared to geofencing road-side technologies. But GNSS positioning in cities remains challenging, because of the poor satellite visibility and of the occurrence of many satellite signal reflections (multipath), that in the best case combine with the direct signal, but, when the direct signal is obscured, create significant biases of several tens of meter in the pseudo-range measurements and consequently on the computed position.
The method proposed here is based on a simplified 3D model of buildings at both sides of streets, named “Urban Trench” for that reason, which can benefit in the process of satellite visibility check and GNSS positioning. Homogeneous street sections are described with three parameters: width, building height and transversal position of the vehicle. These parameters allow to identify the satellites in direct visibility and to compute the estimated additional range brought by the reflections. It has been proved that, in some environments such as the Grands Boulevards in Paris, the position computed by a least squares method can be improved by a factor of 70% after application of our visibility check and multipath bias correction, without degrading the availability..

Keywords: geofencing; GNSS accuracy; multipath; 3D city model.

Résumé

La taxation des déplacements mesurés par GNSS est assurément un levier puissant de régulation du trafic et de financement des infrastructures, sans avoir besoin d’équipements de bord de voie. Mais le positionnement GNSS en ville reste difficile, à cause de la faible visibilité et des réflexions du signal sur le bâti (multi-trajets). Celles-ci au mieux se combinent avec le signal direct, au pire, quand le signal direct est masqué, créent des biais de plusieurs dizaines de mètres sur la mesure de pseudo-distance et la position calculée au final.
La méthode proposée ici est basée sur un modèle 3D simplifié du bâti de part et d’autre des rues, dénommé “Tranchée Urbaine” pour cette raison, et dont on bénéficie en termes de test de visibilité satellitaire et calcul de position. Des sections de rue homogènes sont décrites par trois paramètres: largeur, hauteur du bâti et position transversale du véhicule. Ces paramètres permettent d’identifier les satellites en vue directe et d’estimer les trajets additionnels fait par réflexions. Dans des environnements comme les Grands Boulevards à Paris, on a montré que la position calculée aux moindres carrés peut être améliorée de 70% après application de nos tests de visibilité et nos corrections de biais, sans dégradation de la disponibilité.

Mots-clé: geofencing ; précision des GNSS ; multi-trajets ; modèle 3D urbain.

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1. Introduction

GNSS systems have significant potential in the development of Intelligent Transport Systems (ITS) 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 of the position, 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 centers, the propagation phenomena in the surrounding of the antenna, more precisely diffraction and multipath are responsible for severe errors on the raw observables that are measured by the receivers (Braasch, 1996). The most severe deviations (up to several tens of metres on pseudo-ranges measurements) 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 methods of computing a position and the associated protection level coming from the civil aviation community (MOPS, 2006) are no longer adapted and it is necessary to develop new methods customized to the specificity of the terrestrial environments, especially urban environments.

2. State of the art

2.1. SBAS error models and RAIM

Satellite-Based Augmentation Systems, like EGNOS, is the usual method for improving Quality of Service of GNSS receivers, and particularly their accuracy and integrity. All the signals covering a continent are permanently monitored, in order to detect any abnormal behaviour and to update the error models at the raw measurements level, these error models being finally used by the Integrity Monitoring module to estimate a reliable protection level supposed to over bound the error at the position level (Brown, 1996). This has been designed for the civil aviation context, and does not pay attention to multipath error sources locally, with typical measurement biases.

FDE (Fault Detection and Exclusion) is another mechanism for integrity monitoring developed by the civil aviation community, more known under the name of RAIM (Receiver Autonomous Integrity Monitoring). FDE is totally autonomous since it is based on statistical tests applied to the available measurements. This mechanism start to be implemented in the navigation software of some receivers, coupled or not with instruments like odometer or gyroscope commonly used in the automotive sector (Gao et al., 2006 and le Marchand et al., 2009). They help in preventing corrupted observations to false the navigation solutions, but they are based on 2 hypotheses: a good redundancy and no more than a unique defect at the same time, which is generally not satisfied. In addition, unbiased normal distributions are again assumed.

2.2. Map aided solvers

Another approach takes advantage of the digital map constraints corresponding the domain where the navigation solutions should lie, e.g. a network of streets in cities and road maps in general. The positioning problem can, for instance, be solved using particle filtering in which the particles leaving the road are eliminated (Toledo-Moreo et al., 2009).

For a few years, in addition to navigation process improvements, researchers, have addressed the use of 3D models of the environment to analyze reception conditions and mitigate multipath phenomena: Bradbury et al. (2007), to the best of our knowledge, was the former. But the initial point where to compute the local geometry is a tricky problem! Additional information through vision brings about operational applications: in (Meguro et al., 2009), the authors use a fish-eye infra-red camera to map the satellite positions with respect to the surrounding buildings. More recently, the CAPLOC project (Marais et al., 2012) addresses this issue for guided transport in urban environments, using also a fish-eye camera on the vehicle and aiming at building in real-time a 3D model from the successive images. Without vision, car turn rate and wheel speed sensors are of great interest, as well as road constraints: actually (Obst et al., 2012) suggests ray-tracing in a simplified 3D model of buildings, whilst (Peyret et al., 2011) relies on a very sophisticated data base.

3. The urban trench model

Previous works proved that a priori knowledge of the environment is of great use to characterize conditions of GNSS reception, leading to a significant improvement of the observables quality and, as a consequence, the quality of the computed position.

The research investigations reported in this communication addresses a new way 3D map data can improve the positioning computation, by both GPS raw data filtering and correction. The information contained in the map has been designed as simple as possible, so that it matches the requirement of usual embedded and navigable maps. This information should actually be registered as a set of attributes applicable to the standard polyline structure of digital maps.

3.1. The width, (W), height, (H), and lateral position, (P), urban trench parameters

The first step of the method consists in a characterization of the environment, defined by the triplet of parameters (W=Width of the street, H=Height of buildings, P=lateral Position of the vehicle). All the circuit that will be travelled by the vehicle is divided into homogenous sections having approximately the same constant geometric features: width of the street and height of the buildings, plus – last but not least – the lateral position of the receiver in the street whilst travelling there. 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 circuit is identified by a locally applicable triplet.
This 2D characterization is embedded into the navigation database in order to give, for each satellite, at each time, the urban configuration surrounding the satellite receiver.

3.2. 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 namely an "Urban Trench", defined by the triplet of parameters (W, H, P), of infinite length, in which the satellite receiver is in the center. (Note that the height of the antenna above the ground is deducted from H.) From this model, the algorithm of the "mask of visibility" discriminates the satellites in LOS from the satellites in NLOS. 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 (W, H, P);
- β 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.

A deterministic computation of the number of reflections performed by the signal can easily be made, under specular reflection hypothesis, knowing the azimuth and the elevation of the satellite. The number of reflections that may occur is supposed not to exceed 3. The algorithm is summarized for the two possible cases (left and right) in Table 1. (Note that P is replaced by (1-P) between left and right sides.)

Table 1. Definition of the critical elevation angle, i.e. the elevation angle under which 1 reflection occurs, and similarly for the occurrence of 2 and 3 reflections.

For the satellites situated on the left side of the street	For the satellites situated on the right side of the street
$-\pi \le \beta \le 0$ or $\pi \le \beta \le 2\pi$	$-2\pi \le \beta \le -\pi$ or $0 \le \beta \le \pi$
$el_1 = el_b = arctg\left\lvert \frac{H}{PW} sin(\beta) \right\rvert$	$el_1 = el_b = arctg\left\lvert \frac{H}{(1-P)W} sin(\beta) \right\rvert$
$el_2 = arctg\left\lvert \frac{H}{(2-P)W} sin(\beta) \right\rvert$	$el_2 = arctg\left\lvert \frac{H}{(2-(1-P))W} sin(\beta) \right\rvert$
$el_3 = arctg\left\lvert \frac{H}{(2+P)W} sin(\beta) \right\rvert$	$el_3 = arctg\left\lvert \frac{H}{(2+(1-P))W} sin(\beta) \right\rvert$

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"). An illustration obtained by such method is given in Figure 2, corresponding to the street configuration depicted in Figure 1.

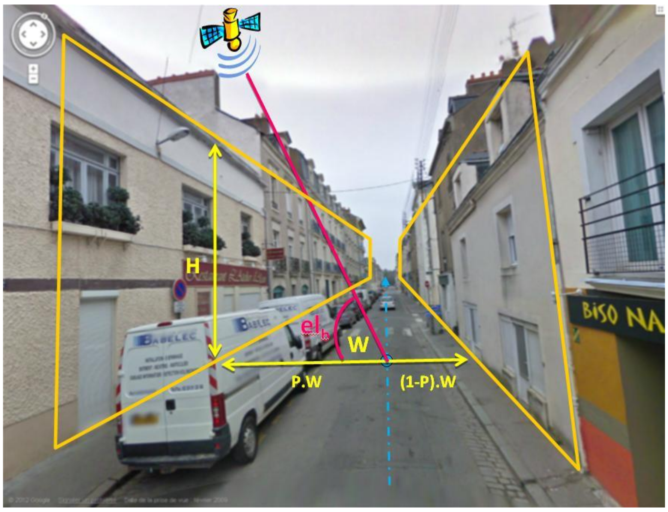

Fig. 1. Overview of the characteristics of a street in Nantes (W=10 m, H=8 m, P=0.5), typical of an urban trench.

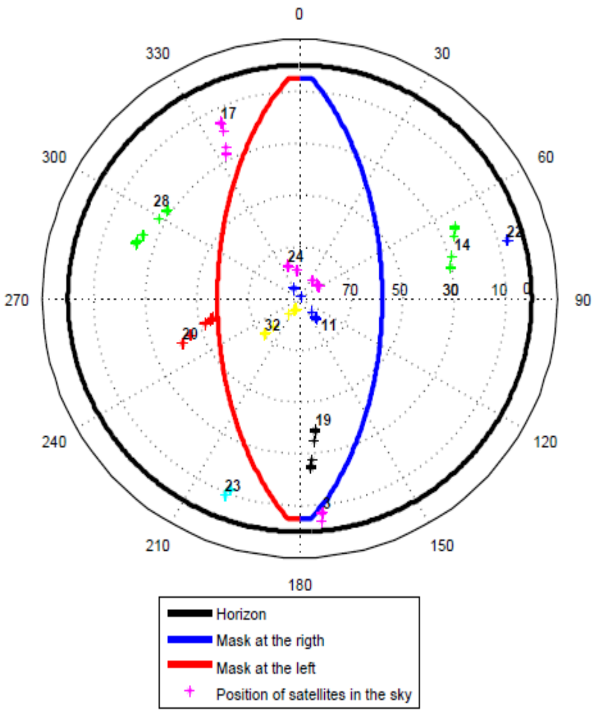

Fig. 2. The corresponding mask of visibility.

3.3. The additional distance

Once the number of reflections has been determinated, the additional path Δ_d performed by the signal can easily be computed, as shown in Figure 3. Geometrical rules of specular reflection apply.

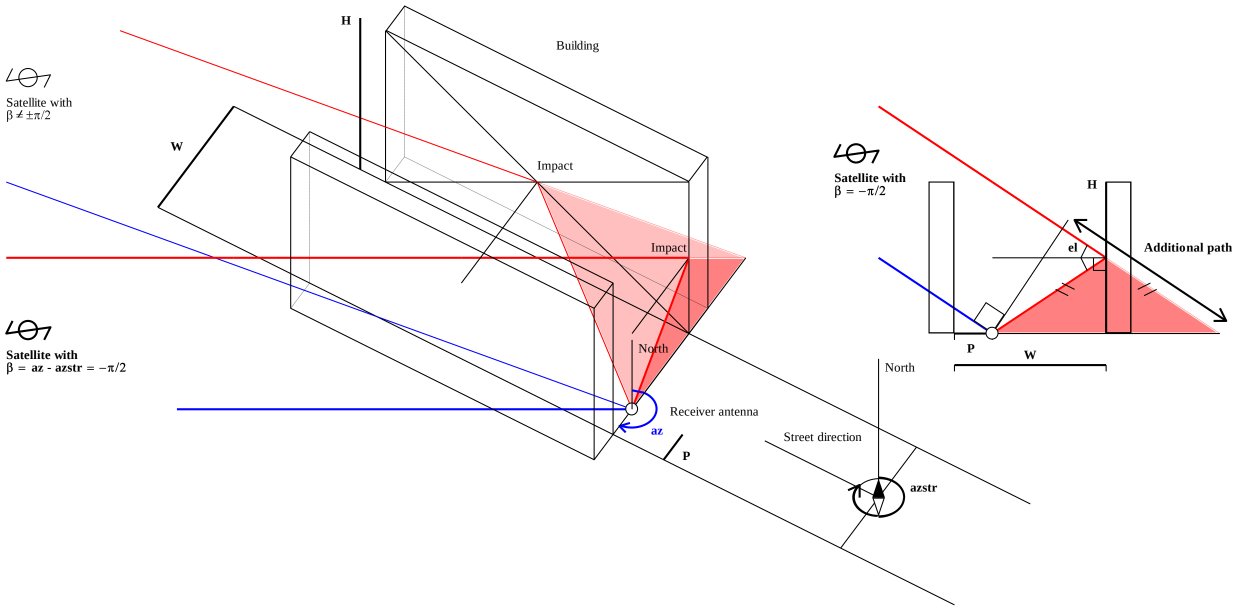

Fig. 3. Urban trench W, H, P triplet and 2 NLOS satellites: one with an azimuth orthogonal to the street direction, i.e. β=-π/2.

Table 2 gives the additional distances corresponding to 1, 2 or 3 specular reflections. Note that an even number of reflections will make a similar additional distance for both sides of the street

Table 2. Additional signal travelled distances for 1, 2 and 3 reflections resp.

For the satellites situated on the left side of the street	For the satellites situated on the right side of the street
$-\pi \le \beta \le 0$ or $\pi \le \beta \le 2\pi$	$-2\pi \le \beta \le -\pi$ or $0 \le \beta \le \pi$
$\Delta_{d1} = 2W(1-P)cos(el)sin(\beta)$	$\Delta_{d1} = 2W(1-(1-P))cos(el)sin(\beta)$
$\Delta_{d2} = 2Wcos(el)sin(\beta)$	$\Delta_{d2} = 2Wcos(el)sin(\beta)$
$\Delta_{d3} = 2W(2-P)cos(el)sin(\beta)$	$\Delta_{d3} = 2W(2-(1-P))cos(el)sin(\beta)$

4. Experimental validation

4.1. The LOS-only and mixed solutions

The navigation process chosen is a basic un-weighted least squares solver, with no filtering like Kalman, in order to emphasize the impact of the satellite LOS/NLOS separation. It runs epoch per epoch with a strategy that is twofold:

- First, LOS-only: one computes solutions at the epochs when at least 4 LOS satellites remain after NLOS satellites have been removed, which diminishes the availability of the final position;
- Second, mixed: the NLOS pseudo-range measurements are kept in the computation, but they are corrected in accordance to the local geometry characterized by Urban Trench modeling.

They are introduced progressively, starting from the highest elevation with 1 reflection, plus 2 and 3 reflections if needed, and applying the additional distance correction corresponding.

4.2. Experimental set-up and test cases

VERT, the Ifsttar Geolocalization test vehicle (cf. Figure 4), has been equipped with an IXSea inertial unit, and a dual-frequency Novatel GPS receiver. In post-processing with a base station, this equipment makes it possible the determination of the trajectory performed with an accuracy of less than 10 cm. The receiver and antenna in test are set up on board too.

The leverarm (i.e. the 3D vector) between the Novatel antenna and that of the receiver in test being compensated, the “true” position of the antenna of the receiver in test is finally determined.

Fig. 4. Vert, the Ifsttar Geolocalization test vehicle.

First tests were performed in Nantes for feasibility purpose, in the residential *Ile de Nantes*, for 20 minutes, from which 5 minutes were included in urban trenches. Then in Paris, *XIIth district*, 2h½ (40 minutes in urban trenches) and *Haussmann Grands Boulevards*, 5h½ (3h¼ in urban trenches), and in the business centre of *La Défense*. In the later, it was not possible to define properly any urban trench. Lastly, a test case of 45 minutes was made in the city centre of Toulouse (20 minutes in urban trenches), with a building architecture very different from Paris and Nantes. Tables 3a to 3d gives the results obtained in the different test cases.

Table 3a. Results in Nantes (feasibility test).

	ALL SVS SOLUTIONS			LOS ONLY SOLUTIONS			
nb of ep.	av. %	nb. svs.	error med.	av. %	nb. svs.	error med.	gain
1455	100%	7.2	8.3 m	88.1%	5.76	5.0 m	39.5%
				MIXED SOLUTIONS			
				av. %	nb. svs.	error med.	gain
				100%	5.81	5.4 m	35.1%

Table 3b. Results in Paris XIIth district.

	ALL SVS SOLUTIONS			LOS ONLY SOLUTIONS			
nb of ep.	av. %	nb. svs.	error med.	av. %	nb. svs.	error med.	gain
11635	100%	7.3	22.4 m	68.6%	5.1	6.1 m	72.6%
				MIXED SOLUTIONS			
				av. %	nb. svs.	error med.	gain
				100%	5.3	8.5 m	61.9%

Table 3c. Results in Paris Grands Boulevards.

	ALL SVS SOLUTIONS			LOS ONLY SOLUTIONS			
nb of ep.	av. %	nb. svs.	error med.	av. %	nb. svs.	error med.	gain
57938	99.7%	7.3	32.9 m	82%	4.84	8.8 m	73.3%
				MIXED SOLUTIONS			
				av. %	nb. svs.	error med.	gain
				99.7%	4.88	9.9 m	70.0%

Table 3d. Results in Toulouse.

	ALL SVS SOLUTIONS			LOS ONLY SOLUTIONS			
nb of ep.	av. %	nb. svs.	error med.	av. %	nb. svs.	error med.	gain
5 845	100%	7.6	23.7 m	69.5%	5.5	14.5 m	38.7%
				MIXED SOLUTIONS			
				av. %	nb. svs.	error med.	gain
				100%	5.7	16.0 m	32.6%

In term of positioning accuracy, the gain – in the streets where the model applies – has been experimentally valued at between 30% in Nantes and Toulouse, and up to 70% in Paris, with the same availability as with a standard solver considering all satellites (cf. Figures 5a to 5d).

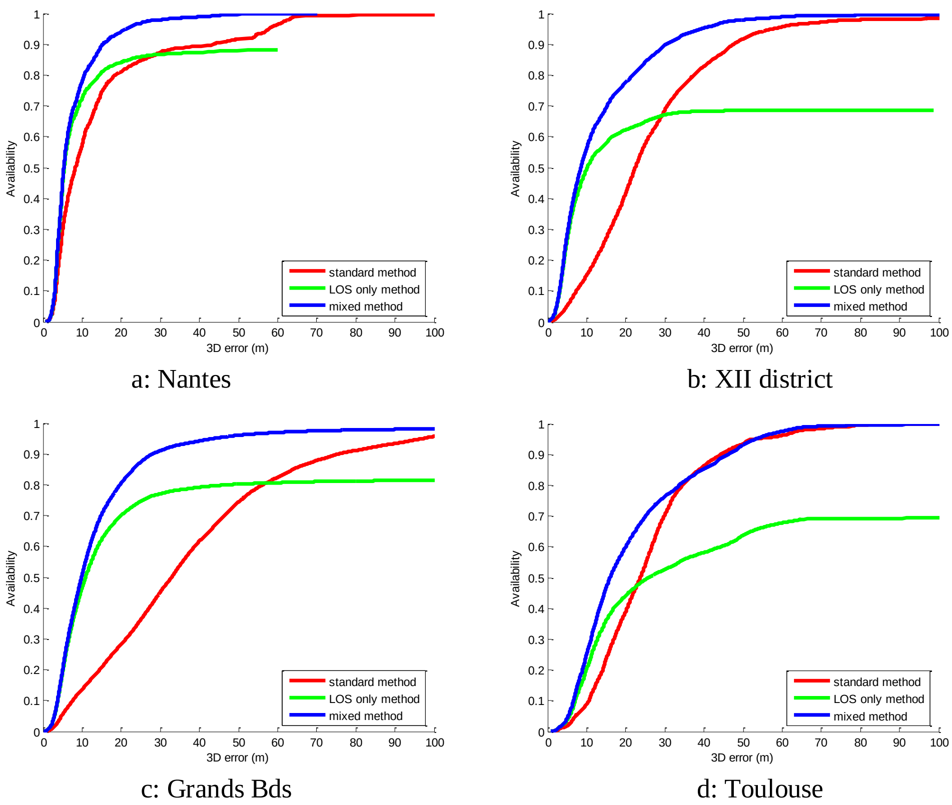

Fig. 5. Cumulative distribution functions of the absolute error in 3D for standard and Urban Trench solutions, in Nantes, Paris XIIth district, Grands Boulevards, and Toulouse.

5. Conclusions and perspectives

The Urban Trench Model and a verification of its ability to enhance accuracy and availability are the main contributions of the paper. An improvement of up to 70% of the 3D positioning accuracy has been obtained in Paris Grands Boulevards, with the same availability as a standard solution. The method is potentially applicable in other cities with similar urbanisation.

Further steps in the process are twofold :

- suggest an algorithm that automatically determine the Urban Trench Model parameters starting from a usual 3D city model;
- test the sensitivity of the method with respect to the lateral position of the vehicle, and develop a multiple hypotheses strategy for that purpose.

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