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Non-Line-Of-Sight GNSS signal detection using an on-board 3D model of buildings

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Abstract—In the context of mobile robot applications for public transportation in cities, there are many challenging issues, one of these being the ability to guarantee a continuous positioning with an acceptable and controlled level of uncertainty under poor conditions of satellites visibility. In the meanwhile, the local environment is more and more accurately described with the very last geographical data bases. The idea that has been studied and implemented at IFSTTAR consists in detecting and eliminating among current GPS raw data the possible Non-Line-Of-Sight satellite measurements, using the knowledge of the 3D environment around the vehicle. The paper describes the principle of the method, its validation and the promising results that have been obtained on the resulting PVT solution. Next step will be the final real-time demonstration of the French National project CityVIP next summer in Paris.

Keywords: *GNSS navigation, map-aided location, 3D city model, NLOS satellite signal*

I. INTRODUCTION

GNSS systems, in particular EGNOS and Galileo, both conceived as major transportation infrastructures, have significant potential in the development of Intelligent Transport Systems (ITS) and associated services.

A major technical issue with respect to mission (e.g. safety and liability) critical applications 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. The integrity confidence indicator, generally expressed in the form of a Protection Level (horizontal or vertical), is a threshold that the actual position error is not supposed to exceed with a given probability. SBAS systems, like EGNOS in Europe, propose a method [1] to compute Position-Velocity-Time (PVT) solutions, together with horizontal and vertical protection levels, customized to the civil aviation needs. This method assumes certain levels and probability laws for the pseudo-ranges errors that are not satisfied at all in many land, and especially urban, environments.

In strongly constrained environments, 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 computed by the receivers. 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 the frame of a collaborative French research project, called CityVIP, the authors have developed a straightforward but innovative method for the detection of the NLOS signals, made possible nowadays by the availability of accurate 3D data bases of the surrounding buildings, that can be embedded in on-board navigation systems, like BATI 3D in Paris, a new product that is being developed by the French National Survey Institute (IGN). The objective of the method is to improve the position and protection levels computation process by detecting and eliminating in real-time the NLOS signals thanks to the 3D data base.

II. STATE OF THE ART

It goes beyond the scope of this article to detail the various techniques that were designed by the manufacturers of GNSS receivers for multipath mitigation (a well-known synthesis [2] can be quoted here). We will just mention that they generally address either antenna or correlator technologies. Actually, most receivers, even mass-market OEM ones, have already embedded multipath rejection tracking loops. Antennas also benefit from polarity selective gain patterns, notwithstanding that certain patch antennas still remain – by design – highly sensitive to any signal, whether it is direct or reflected.

Navigation algorithms have also a game to play in addition to GNSS hardware design for multipath mitigation. Years of research on positioning integrity have yield to the achievement of reference documents among which the DO-208 recommendations for GPS aid in civil aviation where RAIM was first introduced [3].

Once pseudo-ranges have been made available for position and time computation, failure detection is the first integrity test level: in a few words, the normalized sum of the squared residuals is compared to a χ^2 threshold with $N-4$ degrees of freedom (N being the number of satellites in view) and a given probability of false alarm.

At a more advanced integrity test level, FDE (Fault Detection and Exclusion) consists in identifying one faulty measurement in the redundant data set. Note that a unique default assumption is made. A protection level can be computed after possibly removing one observation. For further reading on RAIM techniques, please refer to [4].

None of these techniques works well in urban navigation where multipath is the key problem and causes several faulty measurements at a time. As this is suggested by [5], an alternative approach (instead of standard FDE that cannot work under a limited number of satellites) consists in a characterization of the solution error (based on residuals) and the provision of a protection level with all satellites in view. As a matter of fact, this level is generally larger than if exclusion was done, which obviously leads to reduced application availability. But once again, at least 5 satellites are required to figure out positioning system residuals.

One can also tackle the integrity problem from the angle of measurement error characterization (and particularly pseudo-range). A recent study [6] showed the importance of NLOS multipath as a source of measurement faults. In his PhD dissertation, Le Marchand proposed advanced FDE methods that take advantage of either vehicle odometry or multiple epoch horizon, both methods being finally combined with maximum redundancy.

Advanced signal processing have also been applied to pseudo-ranges in order to characterize their error, this being obviously non Gaussian in case of NLOS. [7] proposed a Gaussian mixture model for range error (operated in a jump-Markov navigation process), and more recently [8] obtained more promising results with a Dirichlet process mixture model (operated in a particle filter), but the implementation of such algorithms in GNSS receivers is still a tricky problem.

To conclude, NLOS signals still remain the major issue since they are often considered as direct signals by mass market receivers using low-cost antennas. In order to go beyond autonomous integrity limitations, we propose to consider the problem in a 3D described environment, where, starting from one's location, possible NLOS satellites could be identified. The LocoPROL project [9] already used an obstacle elevation model from both sides of a railway: we here generalize the concept to any location in a 3D modelled urban centre.

III. THE CITYVIP PROJECT

A. The project

CityVIP is a French cooperative research project funded by the ANR (National Research Agency in France), lasting from July 2008 to December 2011 and gathering 8 partners, well-known in the domain of mobile robotics and geomatic engineering. It aims at developing and demonstrating various functions that are critical for future individual public transportation concepts in cities, based upon small automated individual vehicles. The main functions addressed by the project are: path planning, automatic navigation, obstacle detection and accurate positioning with integrity.

The main innovation of the project lies in the possibility of exploiting the 3D description of the environment provided by IGN partner (National Geographic Institute), through the embedded Geographical Information System (GIS) provided by partner BeNomad. These map data can be used at different levels by different processes, in particular by the process of filtering the observables coming from NLOS signals. This process is described below.

B. Positioning in CityVIP

The quality of the positioning is indeed the key for being able to navigate automatically in a complex environment like a city. But the bad news is that, in such environments, the positioning is even more challenging, due particularly to the very poor availability of GNSS. In the CityVIP project, gathering experts in vision-based positioning as well as experts in GNSS-based positioning, it was decided to merge both technologies to address our challenge, expecting GNSS to provide access to the global reference system when satellite availability is acceptable and vision to provide accuracy when images are good enough and continuity when satellite availability is poor.

Therefore, the positioning system of CityVIP will be based on a tightly coupled estimator, making profit of all available data, sensor data acquired in real-time and a priori data under the form of the 3D map. Since we can easily foresee that the satellite availability will be poor, and even more if we detect and suppress the observables computed from NLOS satellites, the final strategy of the partners in charge of the positioning system in CityVIP is to take into account the GNSS data in the estimator under a tightly coupled scheme, that is to say, with a correction step each time an observable coming from a valid satellite (LOS) is available. The next sections will present the method we developed and the results achieved so far in the project.

Fig. 1 presents the situation of the NLOS filter module in the global position estimation process.

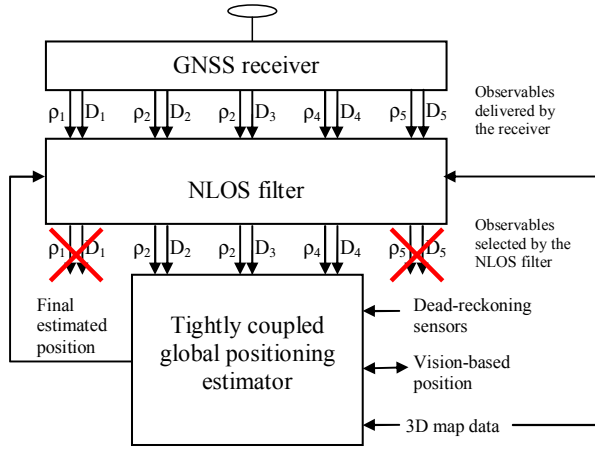


Figure 1. Situation of the NLOS filter in the global positioning estimation chain

IV. PRESENTATION OF THE NLOS DETECTION METHOD

The purpose of the method is to detect if a satellite from which the signal is received by the GNSS receiver is NLOS or not (LOS), by using the knowledge of a 3D model of the environment, before using the corresponding raw data in the PVT computation. The 3D model is stored inside the CityVIP GIS and only contains the roads, the surrounding buildings with no description of the vegetation. The accuracy of the model is: 5 cm horizontally and 25 cm vertically. Coordinates are expressed in Lambert 93 national projection, plus the altitude as third coordinate.

The method is quite straightforward. The first step consists in determining the geographical positions of both the user antenna and the satellite we want to test. In the final stage of the project, the position of the antenna will come from the CityVIP positioning system fusing data from GNSS, dead-reckoning sensors and vision-based algorithms, under the 3D map constraints. Then, we determine, with respect to the azimuth angle of the satellite and thanks to the embedded 3D model, which is the critical elevation angle imposed by the environment. 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.

A. Position of the user antenna

At the time we write this article, the final position estimator of CityVIP, still under development, is not available. Consequently, we used in our experiments our Reference Trajectory Measurement (MRT) system to produce the antenna position that feeds our NLOS filter. This tool is described in <http://www.gnss-test-portal.eu/tools/view/43>.

In this respect, we recognize that the results we show in this paper might be less convincing in the final system, where the error on the final estimation might bring an error in the NLOS detection itself, with a

possible divergence risk that will have to be studied in the next phase of the project.

B. Position of the satellites

In a real time process, the simplest way to access to the position of the satellites is to extract them from the NMEA GSV frame provided by the receiver. Off line, we can use the daily broadcast ephemeris available from the IGS web site and the raw data stored from the receiver, translated into the RINEX format, to compute the satellite positions thanks to the standard method explained in [10].

Then, knowing the position of the GPS receiver and the position of the satellites, we can determine the angles of azimuth (α) and elevation (β) of all satellites in view.

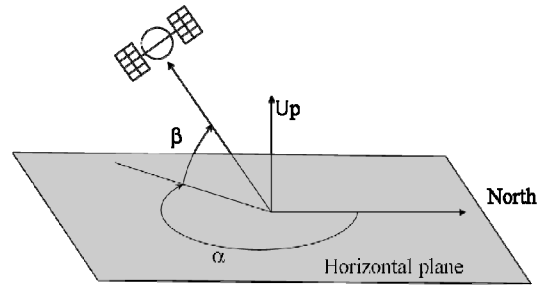


Figure 2. Angles of azimuth α and elevation β

C. Critical angle of elevation

The access to the 3D model data is made by means of graphical card and graphics OpenGL libraries from an own Software Development Kit (SDK) developed by BeNomad. This SDK allows making a graphic depiction of what would see a virtual camera from which we control perfectly the intrinsic and extrinsic parameters.

The extrinsic parameters are defined in the following way:

- the position of the optical centre is given by the precise position of the GPS antenna,
- the orientation is defined in a way that the central pixel of the virtual image points at the direction of the considered satellite azimuth,
- the roll or pitch angles are fixed to zero.

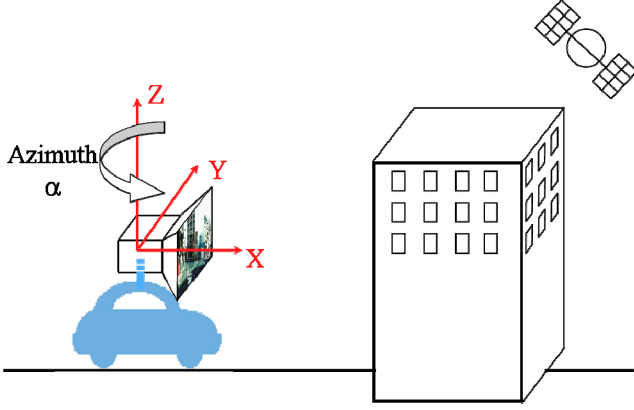


Figure 3. Orientation of the virtual camera, the XY plane is always horizontal.

As intrinsic parameter, the focal distance is set in order to have the top of the frontal buildings into the graphic depiction. This is done automatically, using basic requests of the BeNomad SDK.

This SDK allows the use of functions like:

$\text{GetDepth}(\text{CentralPixel}(X_p, Y_p))$

$\text{Distance}(\text{CentralPixel}(X_{p_m}, Y_{p_m}), \text{CriticalPixel}(X_{p_c}, Y_{p_c}))$

The first function returns the depth in the real world of the point corresponding to the pixel and the second one returns the distance in the real world between two points.

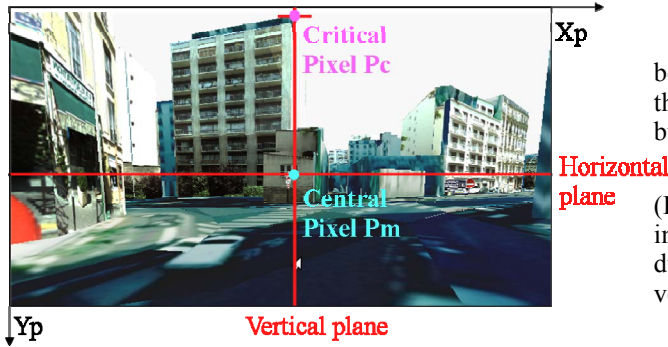


Figure 4. Graphic depiction and the 2 pixels of interest in a current view.

Once the virtual camera is correctly configured (position, orientation, focal distance), we determine the coordinates (X_{p_c}, Y_{p_c}) of the critical pixel situated on the border between sky and surrounding buildings. Knowing the coordinates of this critical pixel, and using the functions described above, we determine (see Fig. 5):

$\text{CentralDepth} = \text{GetDepth}(\text{CentralPixel}(X_{p_m}, Y_{p_m}))$

$\text{CriticalDepth} = \text{GetDepth}(\text{CriticalPixel}(X_{p_c}, Y_{p_c}))$

$D = \text{Distance}(\text{CentralPixel}(X_{p_m}, Y_{p_m}), \text{CriticalPixel}(X_{p_c}, Y_{p_c}))$

The calculation of the critical elevation β_c is made by:

$$\beta_c = \text{Asin}\left(\frac{H}{\sqrt{\text{CriticalDepth}^2 + H^2}}\right) \quad (1)$$

with:

$$H = \sqrt{\text{Distance}(P_c, P_m)^2 - (\text{CriticalDepth} - \text{CentralDepth})^2} \quad (2)$$

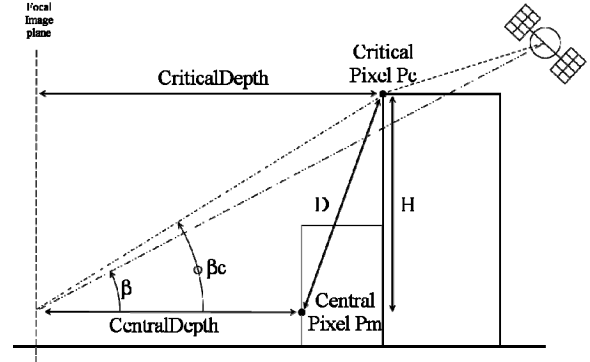


Figure 5. Details of the measurements used.

Finally, there remains the comparison between the critical angle of elevation β_c and the satellite angle of elevation β to know whether the received satellite is:

- LOS : $\beta > \beta_c$;
- NLOS : $\beta \leq \beta_c$.

V. THE BENCHMARKING DATA SET

For validation purpose, a full scale experiment has been carried out in Nantes city centre, in the vicinity of the international events centre, with typically 15 m high buildings and quite narrow streets (15 m maximum).

The VERT vehicle (Fig. 6) was used with its MRT (IVA) equipment on-board, hybridising a high-grade inertial measurement unit (LandINS, from iXSea) with a dual-frequency kinematic GPS and the odometer of the vehicle.

The test campaign consisted in repeating 5 loops (2 in the morning, 3 in the afternoon) in the area, under 2 different constellations. The itineraries are not exactly the same, but their differences are not considered in this study. Each loop is approximately 15 minutes and 10 km long. Static phases occasionally occur, and are observed systematically before and after each loop in order to fix the kinematic GPS ambiguities and achieve centimetre accuracy regularly.



Figure 6. VERT: our experimental vehicle providing ground truth and its on-board IXSEA inertial measurement unit

The area being densely built, kinematic GPS is unstable, and the IMU bridges time intervals of several minutes (maximum) during which ambiguities cannot be fixed. Previous qualification of the MRT equipment proved that the standard plane and vertical errors (with forward and backward fusion process) do not exceed 50 cm and 25 cm respectively during such 5 minutes outage [11]. Moreover, the pure integration of LandINS gyroscopes and accelerometers is in practice well characterized and the positioning error envelop given with the computed trajectory is considered reliable and consistent with the real errors.

VI. RESULTS ON THE NLOS SIGNAL DETECTION

In this section, we analyse the impact of NLOS detection on the data set collected in Nantes, and we also compare this output to that produced by Ergospace® dedicated software using ray tracing technique.

A. Ergospace® software

Ergospace® is a simulation software package dedicated to radio waves propagation in 3D constrained environments [12]. It is able to detect if a satellite is NLOS or LOS and can also determine multipath caused the 3D environment. But this software is not designed to run in an embedded system.

First of all we have integrated the 3D model into the software local ellipsoid tangent frame. Then, the positions of the satellites are computed thanks to almanacs found on the Internet site of the Navigation Center of U.S. Coast Guard: <http://www.navcen.uscg.gov>. Finally the simulated trajectory integrated into Ergospace® is the same as the one used in the BeNomad SDK, i.e. the precise position of the GPS antenna calculated with the MRT reference system.

At each time of the simulation, the Ergospace® software analysis can classify a satellite signal according to 3 different cases, the first two ones being non exclusive:

- direct: the signal from this satellite is received in a direct way, meaning that the satellite is in view of the antenna,
- reflected: the signal is received after n reflection(s) (n max is a simulation parameter that can be chosen),
- no reception: the signal does not reach the antenna, neither in a direct way, nor after any reflection.

B. Results

We used the benchmark data set to compare the results obtained by the two software tools: the one we have developed for CityVIP project and Ergospace®. More precisely, we compared the NLOS signals detected by our algorithm to the ones classified as *reflected* and not *direct* by Ergospace®, and the LOS ones to the ones classified *direct* par Ergospace®.

Next table shows the impact of NLOS detection on our data set. In addition, we have measured the disagreement between our detector and Ergospace® corresponding output, in terms of non detection and false detection, Ergospace® being considered as the reference to compare to.

TABLE I. NLOS DETECTOR IMPACT ON OUR DATA SET AND ANALYSIS COMPARED TO ERGOSPACE®

Description	LEA-4T	LEA-6T
Total duration	15 ' and 15 "	15 ' and 15 "
Number of epochs corresponding (if no total mask had occurred) at 4 Hz	3 660	3 660
Number of epochs actually available for LMS (4 satellites or more)	3 639 (99.4 %)	3 058 (99.9%)
Number of received satellites	31 113	28 494
Number of detected NLOS satellites	7 877 (25.3 %)	5 747 (20.2%)
Number of epochs available for LMS after NLOS detection	3 450 (94.3 %)	3 448 (94.2%)
Number of NLOS signals detected that should not be (vs Ergospace®)	508	444
Number of NLOS signals not detected that should be (vs Ergospace®)	549	482
Disagreement in % of observations	3.4	3.2

(Draft version with loop 3 only, to be completed by loops 1, 2, 4, and 5)

The total test duration was 1 hour and 15 minutes, at 4 Hz, with maximum 2 consecutive epochs missing (while riding under bridges...), otherwise there were always satellites in view and enough (i.e. 4) for LMS solutions.

Since part of further computation for navigation will actually require 4 satellites per epoch, we display in Table I the number of epochs actually available before and after NLOS detection. The maximum mask duration – under 4 satellites condition – raises up to 26 s.

On the other hand, the navigation through a filtered solution bridges observation gaps, whether they are total or partial, irrespective of the number of satellites that remain. The maximum total mask duration never exceeds 3.75 s after detection.

The disagreement of 3% between our NLOS filter and Ergospace® can be easily explained by 2 main phenomena: 1) the differences between the almanacs from the U.S. Coast Guard used for Ergospace® and the ephemeris used for our filter, 2) the digitalization (pixels) of the 3D data in the map.

VII. IMPACT ON THE PVT COMPUTATION

The impact of NLOS filtering on PVT computation is analysed using two different algorithms:

- first, a standard unweighted LMS solution, using pseudo-ranges ρ before versus after NLOS detection;
- second and similarly, an extended Kalman filter (EKF), using pseudo-ranges and Doppler measurements F_d and additional dead-reckoning sensors (KVH fibre-optic gyroscope and odometer of the test vehicle).

Doppler measurements of those satellites that were NLOS identified were removed like the corresponding pseudo-ranges.

LMS algorithm does not require further description.

As concerns the EKF, the state vector contains local ellipsoid tangent plane position, velocity and acceleration, height above the ellipsoid, receiver clock term and drift:

$$x = [E \ N \ \dot{E} \ \dot{N} \ \ddot{E} \ \ddot{N} \ h \ c\Delta t \ c\Delta t]^T \quad (3)$$

The EKF equations are summarized below:

- prediction model: pure integration of East and North accelerations onto which a centred white noise applies, constant height (similarly noised), pure integration of the clock drift onto which another centred white noise applies; if S_p denotes the random walk of the white noise generating a process (like accelerations here) [13], variances and covariances of its integrals can be easily derived, S_p being the only parameter to tune;
- observation model, which is twofold: proprioceptive data (odometer giving speed and gyroscope giving turn-rate):

$$V = \sqrt{\dot{E}^2 + \dot{N}^2} \quad (4)$$

$$\omega = \frac{\ddot{N}\dot{E} - \ddot{E}\dot{N}}{\dot{E}^2 + \dot{N}^2} \quad (5)$$

and exteroceptive data (GPS pseudo-ranges and Doppler measurements, whose observation equations are well-known).

Gyroscope and odometer data are considered to be free of any outlier that would be worth to detect and exclude, which suppose that both instruments will not show any unreliable trend.

An iterative fault detection and exclusion (FDE) strategy is applied, independently for pseudo-ranges and Doppler measurements. In a few words, this consists in computing the Normalized Innovation Square (NIS) and comparing it to a χ^2 threshold for a given probability of false alarm.

In case this comparison proves to be positive, the observation with the highest weighted residual is removed, whether it is a pseudo-range or a Doppler measurement.

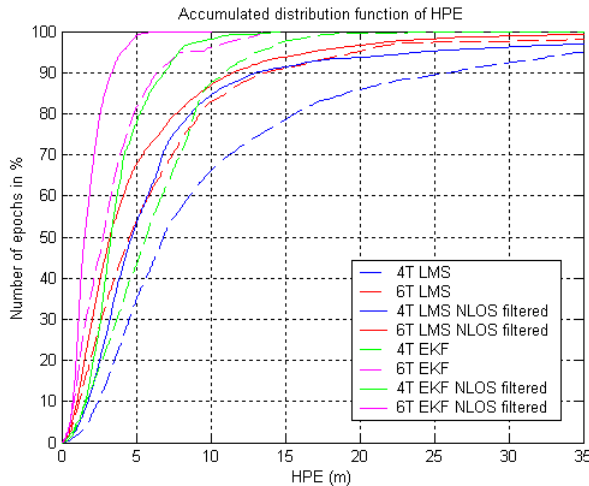
The remaining subset of observations, after possibly several iterations of the above NIS tests, makes the final data set for the Kalman gain computation and state correction.

The tuning of the main filter parameters is the following:

- prediction model: at the filter sampling frequency of 10 Hz, previous tests in similar conditions with the same vehicle made it possible the prediction model tuning with: $S_p = 1 \text{ m}^2/\text{s}^4/\text{s}$ for positioning, and 0.1 m and 0.1 m/s standard errors for receiver clock term and drift, at every sample time;
- gyroscope and odometer: 0.0044 rad/s (from KVH specification of angular random walk) and 4 m/s;
- GPS: 7.5 m for UERE and 0.4 m/s for standard Doppler error;
- probability of false alarm in the χ^2 GPS data tests: 1%.

Additionally, the EKF sometimes needs to be reset. Obviously, this is needed in case of receiver clock term jump. But also in some tricky situations when the FDE strategy fails, which may happen. Actually, misdetection is statistically possible, which entails exclusion of observations that should have been used. In order to prevent the algorithm to diverge, one counts the number of raw data removed epoch per epoch. If this number systematically exceeds a given threshold (e.g. 3 or half the number of satellites) for a given time window (typically 3 seconds), then the filter is reset. This reset has been made possible either on pseudo-ranges or Doppler measurements.

Figure 7 presents the gains in terms of horizontal position error brought by the NLOS filter.



(Draft version with loop 3 only, to be completed by loops 1, 2, 4, and 5)

Figure 7. Gains in terms of error on the horizontal position error brought by the NLOS filter.

The gains brought by our filter can be easily seen on the figure, whatever the receiver and the PVT computation method. With the u-blox LEA-6T receiver, the accuracy at 95% goes below 5 m, which is indeed an interesting performance in such environments. Last, but not least, the EKF reset occurrence has been significantly reduced thanks to NLOS satellites detection.

VIII. CONCLUSION AND PERSPECTIVES

We have introduced a new method for NLOS signals mitigation at the raw observables level, making profit of the knowledge of the environment of the antenna thanks to a 3D model accessible through a dedicated GIS.

This method has been checked versus commercial ray tracing simulation software and has proved to be quite efficient in terms of error reduction, whatever the PVT computation algorithm. The gain is even more obvious with EKF filter using additional dead-reckoning sensors, this method bringing additionally a significant gain on availability too.

For the study we presented here, the position we used as input for the NLOS filter was the position provided by the reference trajectory. In the future CityVIP system that will be demonstrated, the filter will run in closed loop, meaning that the “true” position will be replaced by the best real-time estimate of the position which will

show less accuracy, creating possible risks of instability we will have to study in the next step. The final version of the NLOS filter will be demonstrated together with the other components of the CityVIP project in September 2011.

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