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# How to Assess and Improve Satellite Positioning Performances in Urban Environments

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## BIOGRAPHY

Grégoire Duchâteau is Eng. graduated from Sup'Aero (Toulouse). He joined Alcatel in 1991 and has worked in several areas related to fault tolerance, supervision and control for both wireless telecommunication and transport (rail, road, space) applications. Since 2003 he is technical manager of the Transport solution developed by the navigation business unit of Thales Alenia Space France.

Olivier Nouvel is a Radio Navigation Engineer at M3Systems (Toulouse) since 2002. He is involved in various Radio Navigation projects (GPS, SBAS, GNSS2...) and is specialized in modeling and simulation of RN signal processing chain (Galileo signals, effect of interference/multipath).

Willy Vigneau is head of the Radio Navigation Unit at M3Systems. Graduated as a telecommunication engineer from Sup'Aero in 1999, he joined M3S, a French SME involved in various RN projects: GPS/EGNOS/Galileo signal processing and critical applications of GNSS.

David Bétaille is a researcher in the Division for Metrology and Sensor Instrumentation of the LCPC, where his current activity relates to vehicles positioning by satellites systems combined with dead reckoning and mapping. Advanced Driving Assistance Systems and more generally road safety applications compose the research context of his lab. He received his PhD in 2004 for his investigations at University College London on phase multipath in kinematics GPS.

François Peyret, ENSMA-Sup'Aero Eng. 1973, is Director of Research (equivalent of Professor), and head of the "Image processing and geopositioning" research team, at the Laboratoire Central des Ponts et Chaussées, where he is leading research activities in the field of road vehicle positioning for ADAS, especially with hybrid GNSS systems and enhanced 3D map-matching.

Hugues Secrétan is an expert in satellites navigation systems. He joined the CNES (the French Space Agency) in 1983 after graduating with a degree in electrical and mechanical engineering. He works in the ESA EGNOS Project Office in Toulouse since 1998. He is now in charge of the SPEED system aiming to support the European GNSS Evolution Program launched in 2007.

## ABSTRACT

Satellite positioning performances are critical for transport liability applications such as road user charging, or pay per use assurance. The scientific community has focused for several years on environments with favorable conditions (aviation, maritime, rural) and is now addressing transport applications including urban areas. This is the case of this paper that presents the result of a study co-financed by the National French Space Agency (CNES). This study aimed first to collect the positioning data in urban area of several GPS/EGNOS receivers (more than 1,5 millions of positions) in addition to their associated satellite raw data and the reference positions. Its goal was secondly to assess the performance using classical positioning algorithms and last to propose and assess improved algorithms.

The authors present first how to obtain the true trajectory necessary for the performance assessments. The instrumentation they set-up on board a test vehicle is based on IXSEA LandINS inertial measurement unit hybridized with kinematics GPS and odometry. The reference trajectory obtained is analyzed, with the aim of qualifying its accuracy. Based on these measurements, the authors then present the performance improvements obtained using different techniques, in particular 2D techniques to improve availability in difficult area such as narrow streets, smoothing technique to optimize the filtering and local error modeling technique to assess in particular disturbing multipath effects.

Thanks to the ground truth obtained in this benchmark, the authors demonstrate that these techniques bring a significant improvement to position data performances, enlarging that way the spectrum of liability-critical road transport applications in urban areas.

## 1. INTRODUCTION

Research is extremely active in the domain of positioning systems based upon GNSS and hybridization with other sensors, to cope with the weaknesses of pure satellite systems in constrained environments. In this respect, many research laboratories and industrial companies propose their solution. When time comes for assessing the technical performances of these systems in the environment they have been designed for, generally urban environments, they have to face the difficult problem to establish the true trajectory.

Concerning the true trajectory generally two kind of solutions are proposed: the first one consists in plotting the system output on a digital map and to more or less check that they fit together: it is no use to stress the poor quality of this comparison, especially when you have no idea of the accuracy of the digital map. Moreover, even if digital maps were precise enough, the degree of freedom of the trajectory on the roadway still makes it necessary additional measurements. Hence, the second solution consists in trying to produce an accurate reference trajectory using a kinematics dual frequency GPS trajectory (RTK or PPK). In this second case, the sad thing is that in the environments concerned, the kinematics trajectory, based on phase-differential GPS, is even less available than the code-only solutions.

In a first part, the paper will describe the solution used to get the true trajectory. It is based upon the usage of a navigation-grade inertial measurement unit (IMU) hybridized with a PPK processing and the methodology used for the design of the test circuit. After a brief presentation of the on-board instrumentation, the authors will recall the utilization constraints of the PPK computation, linked to the ambiguity resolution problem and they will introduce the IMU that has been used and its performances, guarantying the required accuracy of 25cm RMS only if the lengths of the PPK position outages do not exceed 3 minutes. The circuits that have been driven in Toulouse will then be described and finally the result in terms of availability and accuracy of the obtained reference trajectory will be presented.

In a second part and based the measurements collected with the true trajectory, the authors then present the performance improvements obtained in urban environments using different techniques that applies to the Position Velocity time algorithms. In particular, the authors presents 2D techniques to improve availability in difficult area such as narrow streets, smoothing technique to optimize the filtering and local error modeling technique to assess local errors in particular disturbing multipath effects.

In order to assess the different techniques, strictly the same GPS raw data inputs is replayed using different algorithms. The 24 hours campaign of tests used here is much larger than most of preceding experiments and thus leads to more robust results.

Each time the positions are computed, they are compared to the true trajectory in order to assess the position error also called Horizontal Protection Error (HPE). In parallel the unavailability of the positioning technique is assessed by counting the ratio of GPS samples that leads to no position fix over the total number of GPS samples.

## 2. ON-BOARD INSTRUMENTATION

The on-board instrumentation for the reference trajectory is composed of:

- the Inertial Measurement Unit LandINS by IXSEA
- an odometer mounted on the left rear wheel (a wheel that is not engine powered)

- a Septentrio dual-frequency GPS receiver (Novatel 402 GG antenna)
- a Scorpio dual-frequency GPS receiver (same antenna)

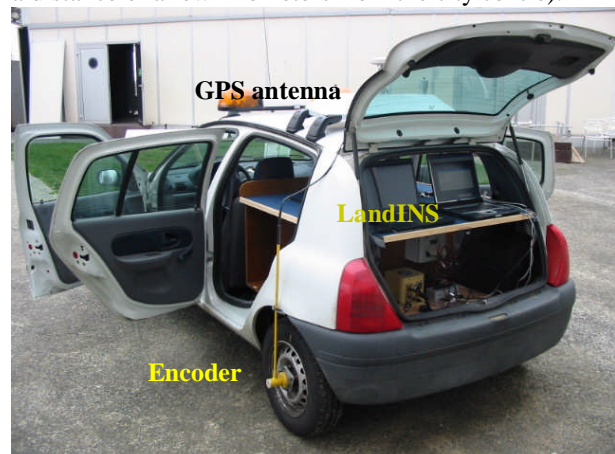
The on-board instrumentation to assess the mass-market receivers is composed of:

- a M3S safedrive product including an ublox receiver TIM-4T
- an Actia TGU product including an ublox receiver TIM-LA and the Thales Alenia Space software "Egnos Inside"
- a laptop PC including the software "Egnos Inside" and connected to an ublox receiver TIM-4T and a Bluetooth Sirf 3 module.

### 2.1 POST-PROCESSED KINEMATIC GPS

The on-board dual-frequency GPS receivers log their raw data of code and phase (convertible in RINEX format if necessary). These data will be post-processed together with similar data collected at a local base station, using THALES GNSS Solutions software: this gives a first PP Kinematics GPS trajectory.

Note that the permanent station *TLIA* of the national network RGP-TERIA has been selected as the base station for post-processing, with a backup solution in Toulouse ENAC (both are permanents stations situated at a distance of a few kilometers from the city centre).



**Figure 1 - the vehicle equipped with Thales Alenia Space, LCP and M3S equipments**

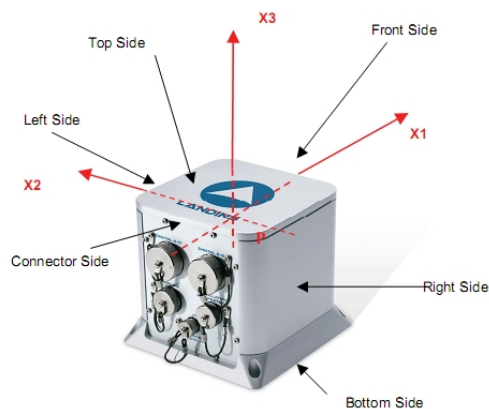
### 2.2 LANDINS Inertial Measurement Unit

LandINS is an Inertial Navigation System built by IXSEA that makes loosely coupling of its own strap-down IMU with GPS navigation points and odometry in Real Time. The IMU contains three pendulum accelerometers and three navigation-grade fiber-optics gyrometers. For specific studies like our where Real Time trajectory is not necessary, the IMU raw data can be logged on a PC terminal for further computation off-line, which makes it possible backward smoothing in addition to the usual Extended Kalman Filter that runs on-board. The post-processing software of LandINS has also been developed by IXSEA and it is called PopINS.



LandINS can work in autonomous mode, i.e. in pure inertial mode. Only the internal accelerometers and gyroscopes are used in this case. This is not the most current working mode. Actually, in order to benefit of the most advanced performances of LandINS, it must be hybridized with a GPS receiver and an odometer. In practice, the pure inertial mode is never activated alone, because whenever the GPS receiver is masked, the odometer continues its measurement of the performed distance.

The IMU materializes a frame, as shown in Figure 1, whose x axis is close to the vehicle forward direction, z axis is close to the vertical when the vehicle pitch and roll are null, y axis makes orthonormal xyz frame.



**Figure 2 - IMU body frame**

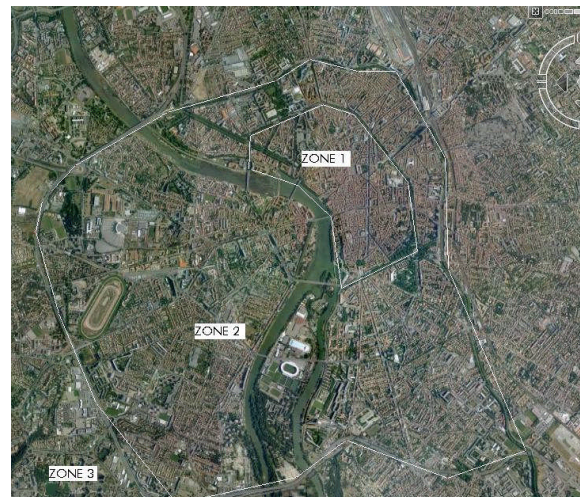
Odometer and primary GPS antenna lever arms are used in the hybridization:

Post Processing PopINS error will remain below 15cm RMS for 2 minutes PPK GPS outage. Actually, backward smoothing bounds the positioning error to the level it reaches at middle of mask duration.

#### 4. METHODOLOGY OF THE EXPERIMENT

In order to enable kinematics GPS ambiguity resolution regularly along the circuit, it appeared necessary to carry out the experiment in stop (2 min) and go (3 min). The weakness of L2 in urban environment causes very difficult “on the fly” ambiguity resolution and LandINS drift would not be acceptable for the assessment of EGNOS (we aim at producing a reference trajectory with maximum deviation below 25cm RMS).

Most of the time was spent in zone 2 (sub-urban area) with several passes in zone 1 (city centre) when the GPS constellation was the best (cf. Figure 5).

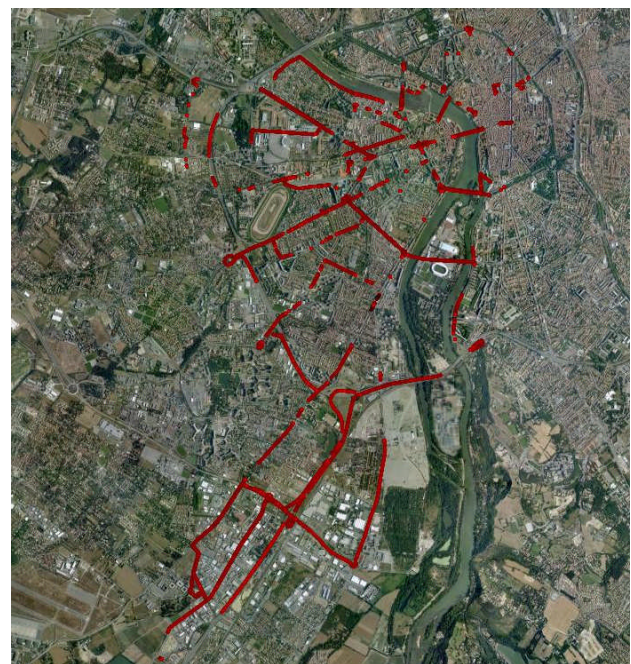


**Figure 3 - city center, sub-urban and rural areas**

#### 5. REFERENCE AVAILABILITY PERFORMANCE

Figures 8 and 9 show on the same map the available kinematics GPS solutions and the ultimate reference trajectory for the total 24 hours campaign of tests.

Over a total distance of 276km in the city of Toulouse, only 95km were covered by PPK GPS, which brings about 35% availability (in distance) only. There are many discontinuities to cope with inertial navigation and odometry. In conclusion, the reference trajectory is available almost everywhere with accuracy < 50cm RMS with LandINS. Last but not least, LandINS is accurately time stamped in UTC time, at a much higher sampling rate (100Hz) than most GPS receivers.



**Figure 4 - PPK solutions only : 35% availability**



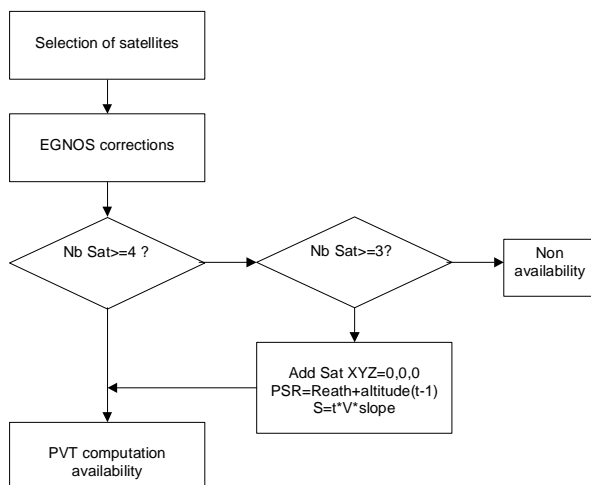
**Figure 5 - Ultimate reference trajectory : almost full coverage, accuracy < 50cm, 100Hz**

## 6. IMPROVEMENT using 2D

The purpose of this activity was to extend the classical position calculation to a 2D position, estimating the altitude from the previous point. The calculation is done as usual (no modification of the Position Velocity Time algorithm) introducing when necessary an additional satellite at the centre of the earth with a pseudo range in accordance with the estimated altitude (see Figure 6).

This gives thus the possibility to get a position using recommended mean-square-value algorithm proposed in the MOPS (The Minimum Operational Performance Standards is the receiver specification to use the EGNOS signal for civil aviation use) even in the case there are only 3 satellites in view.

The objective of this step is to increase the availability of positioning in particular in urban area where the number of satellites in view is reduced due to masking or attenuation effects.



**Figure 6 – 2D High level algorithm**

Using the methodology of the experiment presented in §4, the reference trajectory have been computed for three different runs of 6 to 9 hours each (run #1=9hours; run #2=6hours; run#3=9hours) covering the 24hours of the GPS satellite geometrical configuration. Each time, the position has been computed first using the conventional EGNOS-MOPS position computation and in a second step using the 2D algorithm. The distance between the reference trajectory and the computed position gives the Horizontal Protection Error (HPE).

The table bellow (Figure 7) shows that the unavailability decreased by 30 to 40% using the 2D algorithm at the cost of a slight increase of the HPE. In Figure 7, “HPE 50%” is the median error value and “HPE 95%” is the max error value of 95% of the samples.

The accuracy decreased as it could be expected: all the positions calculated in the MOPS remain indeed unchanged. The table “2D” introduces new positions that are by principle less accurate because they corresponds to position with only 3 satellites in view, so in difficult urban environment with probably poor DOP and high local error (multipath...).

		MOPS		
		Run #1	Run #2	Run #3
HPE	Average	5,76	5,36	8,29
	50%	3,84	3,67	6,11
	95%	15,99	12,37	15,45
Unavailability		5,62	5,47	9,26

		2D		
		Run #1	Run #2	Run #3
HPE	Average	7,01	7,04	10,59
	50%	3,92	3,71	6,22
	95%	17,28	13,30	17,86
Unavailability		3,31	3,74	5,63

**Figure 7: unavailability decreased by more than 30%**

For future analysis, and as a second benefit, the 2D algorithm could be activated even for more than 3 satellites to enable satellite exclusion techniques that require more than 4 satellites in views.

## 7. SMOOTHING TECHNIQUE

This chapter refers to the code carrier smoothing that is used as first phase of the Position Velocity Time computation. The smoothing improves the performances related to the carrier noise ratio C/N0 and to the multipaths.

The smoothing time constant recommended by the MOPS is 100 seconds with inclusion of new satellites after 360 seconds. Such requirements is applicable for civil aviation application where there is almost no masking of the GPS satellites but is very questionable for terrestrial application in urban environment as it leads to less than 15% of availability (measured on the 3 runs of the experiment).



As a consequence, the study logic is to remove the MOPS smoothing technique and to study following other solutions:

- Changing the time constant.
- Including the satellites before the 360s convergence.
- Using a variable time constant

in order to analyze the results in terms of position error and availability.

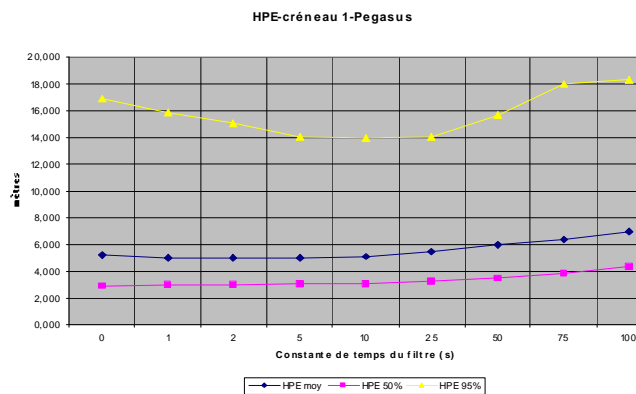


Figure 8: T=25s optimum for Accuracy

Using a filter at 25 seconds is a good compromise to get better accuracy for both average error value and 95% HPE (see Figure 8). But unavailability is still very high (reaching 56,13%) due to the late introduction of the satellites in the positioning algorithm.

As a consequence an additional step has been studied including the satellites before the 360s convergence and using a variable time constant. The result is presented in Figure 9. This new smoothing technique increases significantly the accuracy while preserving a good level of accuracy.

		No smoothing	T=100s	T=25s	T=1s→25s + Use of sat. before convergence
HPE (m)	Average	5.19	6.98	5.43	5.12
	50%	2.92	4.38	3.24	3.33
	95%	16.89	18.30	14.02	15.45
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unavailability (%)		8.12	89.63	56.13	10.38

Figure 9: Increased Accuracy with good availability

## 8. ASSESSMENT OF LOCAL ERRORS

An additional technique to cope with difficult environment is introduced in this section by tackling the local errors.

Many papers are studying the multipath from a theoretical point of view trying to model the 3D environment and potential attenuation in order to predict and estimate the multipath effects from the geometrical GNSS configuration.

Nevertheless, the mass-market receivers do not embed today the 3D model of the streets accurate enough to do this estimation. This is a problem due to both data availability (i.e. it need lots of site surveys and the environment is changing) and terminal capabilities (memory and CPU versus cost).

The approach carried out by the study is based on the experimental data collected during the three runs done in Toulouse. Collecting the GPS raw data, it is possible to extract in post processing the local errors. These errors can be isolated by considering the error correlation between the code and phase measurements (Code Minus Carrier technique). The errors that are introduced by the ionosphere are removed using IGS data and satellite errors are removed using IGS SP3 files.

Once the local error data is available, a correlation is searched with the measurements available in most mass-market receivers (azimuth, C/N0, elevation, heading...).

Our work also concerned studying the error correlation with the (azimuth – heading) value that could correspond to satellites in the axe of the street so potentially satellites that are less affected by multipath. In fact no correlation have been practically found. This result is maybe due to the fact that streets in Toulouse are not very straight and that in average there may be objects/buildings/vehicles producing as much as multipath for the satellites in the direction of move as for the others.

The elevation and C/N0 error correlation study was more fruitful. As shown in the following figures (Figure 10), the error (in red) is following a function of the elevation and C/N0 in particular for high value of C/N0 and elevation (Figure 11).

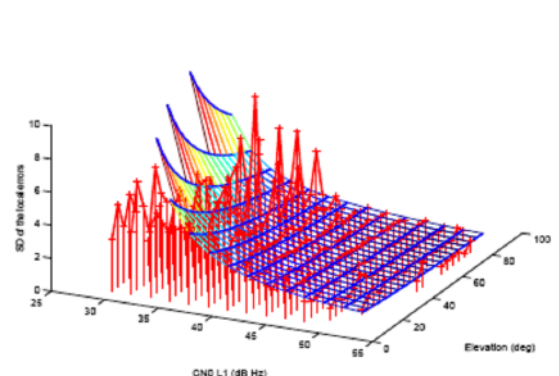
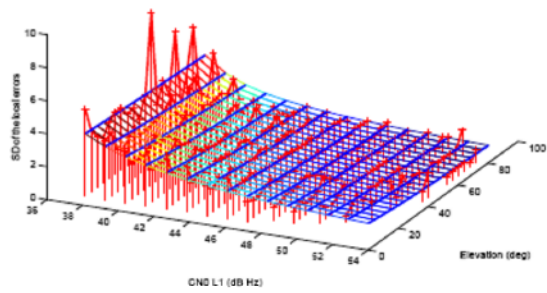
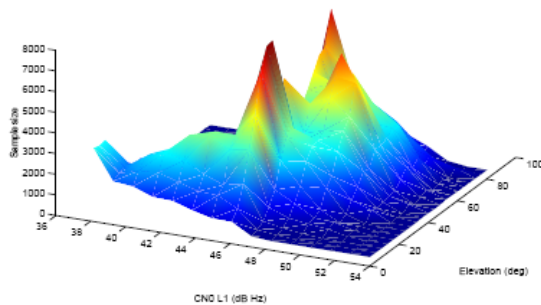


Figure 10: Local error correlation with elevation and C/N0



**Figure 11: Better correlation for  $C/N_0 > 37\text{dB}$**

Nevertheless, this preliminary result must be seen in relation to the currently low number of samples that was available for this study. The model is thus more solid for area where many samples have been collected (i.e. yellow/red area of the Figure 12) and further data collections are necessary to let confirm this preliminary model.



**Figure 12: number of samples per  $C/N_0$  and elevation**

The correlation function found includes 3 constant values (a, b ,c) that may be tuned according to the type of environment and receiver.

## 9. CONCLUSION

This paper presented how to obtain the true trajectory necessary for the performance assessments and how to improve performance using different techniques, in particular 2D techniques to improve availability in difficult area such as narrow streets, smoothing technique to optimize the filtering and local error modeling technique to assess in particular disturbing multipath effects.

These results are the basis for applicable solutions and further studies to let the local error model more robust in all environments and to increase the Position Velocity Time performances (accuracy, availability). This can be reached for example merging these results with additional techniques such as advanced filtering (Particle, Kalman), hybridization with external sensors (Inertial sensors, compass, odometers...) or assistance (Enhanced A-GPS).

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