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Assessment of dynamic geo-positioning using multi-constellation GNSS in challenging environments

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Abstract. Global Navigation Satellite Systems (GNSS) provide accurate and reliable positioning solutions in open field environments. However, the positioning performance is not the same in dense urban areas, where satellite signals are blocked or reflected by tall buildings.

A 3D city model, 'Urban Trench', is introduced to simulate blockage and reflection of GNSS signals. The 'Urban Trench' model assesses the reflection environment of the city and the non-light-of-sight (NLOS) ranging errors are corrected, based on satellite elevation and a 3D surface model. Subsequently, the metric of NLOS signal exclusion using an elevation-enhanced map is developed and tested using real vehicular data in the test urban network of Nantes. A GPS&GLONASS-constellation single-frequency receiver is used during the experiment. The performance of both systems, stand alone and in combination as dual-constellation, are presented, compared and evaluated, with and without 'Urban Trench' model implementation. Additionally, a fault detection and exclusion test is applied, to check and enhance the integrity of the output.

Keywords: GPS, GLONASS, 3D city model, FDE, 'Urban Trench'

1 Introduction

The road applications encompass traditional areas like navigation, guidance, or fleet management, but in future the GNSS will also be part of more sophisticated and intelligent systems. GNSS information empowers automotive services ranging from precise navigation and satellite road traffic monitoring to location-based information services, ameliorating traffic information processing and user distribution [1]. Intelligent navigation systems shall make road safer, minimizing travel time while reducing congestion. As the most cost-effective and performant source of positioning and timing information in outdoor environments, GNSS has become an essential element of major contemporary technology developments notably including the IoT (Internet of Things), Big Data, Augmented Reality, Smart Cities and Multimodal Logistics.

Their potential might have been better exploited by combining different available GNSS constellations. The combination of multiple GNSS can significantly improve mobility applications, as the increased number of satellites strengthens the constellation geometry, resulting in an increased accuracy, while the initialization times are reduced and the overall satellite availability is increased.

The development of real-time kinematic applications in urban areas is very challenging. The arrival of city modelling introduced a possible solution to the satellite propagation signal in urban areas. Buildings are prone to create perturbations in the satellite signal propagation, which makes the positioning solution difficult to obtain and often unacceptably erroneous. Not only may signal paths to the antenna be blocked by obstacles in the satellite directions, but also multipath may occur.

The state-of-the-art focuses on the combination of GPS with the modernized GLONASS satellite code measurements with map-aided data, to bring a light in the road user challenging environment. The performance of the proposed algorithm is analysed using measurements from a low-cost GPS/GLONASS receiver, NVS Technologies AG and a low-cost GPS-only receiver, ublox. Estimated trajectory is compared to a reference trajectory obtained using a geodetic-grade GPS/INS (Inertial Navigation System) [2]. Horizontal error statistics, horizontal protection level will be described for typical urban environments. The area concerned is in Nantes city centre, France.

Overall, GNSS, together with other technologies, satisfies the need of accurate positioning combined with reliability of localisation and improve the efficiency, effectiveness and comfort of road transportation.

2 Position Estimation Algorithms

There are two position estimation methods that are of interest in this research. These methods are the standard ordinary Least-Squares method and the 'Urban Trench' method.

2.1 Standard Ordinary Least-Squares Estimation (LSE)

The satellite positions and observations are read and the following correction are applied [3]: satellite clock corrections, light travel time, Sagnac effect, relativistic correction, troposphere and ionosphere delays.

The least-squares estimator is the most convenient estimator for practical implementations, to guarantee that the linearisation error is negligible. The observation equation is linear only locally, which makes several repetitions mandatory. Finally, point positioning with code ranges is applicable for each epoch separately. Therefore, a position solution is possible in every single epoch, without being in need of previous epochs to estimate the position, as it happens while phase data are processed. Hence, this model may be used in kinematic applications, where direct positioning is essential.

2.2 Urban Trench (UT)

The 'Urban Trench' method uses the city model together with GNSS data to compute the position of the vehicle. D. Bétaille et al., D., in [4], have explored this method. The first phase is the characterisation of 3D environment. Urban canyons have been modelled in a very simple manner, with width of the street (W) and height of the buildings (H).

Thereafter, this geometrical modelling makes the distinction between LOS (Line-Of-Sight) satellite signals and NLOS possible. Removing the NLOS satellites from the final computation is a first solution. However, it dramatically decreases the availability of measurements in dense urban areas. Moreover, the remaining visible satellites are only located along the street direction, which results in a degraded geometry of the usable constellation. The shape of the ellipsoid that statistically encompasses the positioning error is distorted across the street direction, which in consequence makes lateral positioning (and lane determination) very difficult [5]. Therefore, the solution introduced in [4], consists in correcting the range of NLOS satellites assuming specular reflection hypothesis, knowing the azimuth and the elevation of the satellite. NLOS are characterized properly, with their number of reflections (1, 2, eventually 3 in case of a very low elevated satellite). After the detection of the NLOS satellite signals, this

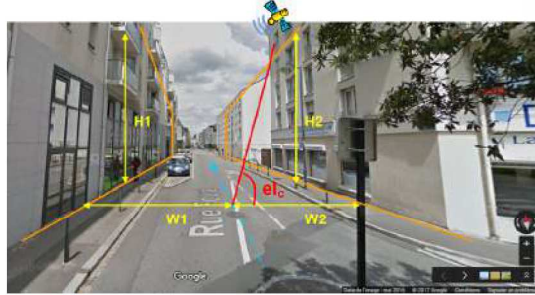


Fig. 1. 'Urban Trench' model applied in rue Foure, in Nantes, [6]

measurement is corrected by applying additional corresponding distance correction. A schematic representation of the algorithm is given in Figure 2. Equations of critical elevation and computation of additional path (m_0 , m_1 and m_2) are detailed hereafter, in Table 1 and Table 2, respectively. Once this is done, the final computation with Ordinary Least-Squares method can be made, using LOS and NLOS satellites. Table 1 gives the threshold in elevation angle below which NLOS conditions, with 1 reflection, are met (and similarly for 2 and more reflections). el_{01} defines the critical elevation angle separating signals with 0 and 1 reflection (LOS and $NLOS_1$). el_{12} defines the critical elevation angle separating signals with 1 and 2 reflections ($NLOS_1$ and $NLOS_2$). W_1 , W_2 , H_1 and H_2 denote the left and right width and height of the urban trench. The width

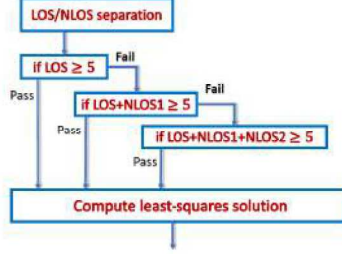


Fig. 2. Schematic representation of the 'Urban Trench' algorithm

is measured from the road centre line to the buildings located in the street on the corresponding side. Both sides are considered and the urban trench can be asymmetric. The road line is arbitrarily oriented similarly as its initial and final points are stored in the database. The azimuth of a satellite with respect to the street direction is β ¹ and its elevation el .

The solution suggested uses LOS satellites and as many NLOS ones as necessary to obtain at least the five satellites needed for a least squares estimation. The computation for the positioning solution uses the Ordinary Least-Squares method.

Left side		Right side	
$el_{01} = \arctan \left \frac{H_1}{W_1} \sin(\beta) \right $		$el_{01} = \arctan \left \frac{H_2}{W_2} \sin(\beta) \right $	
$el_{12} = \arctan \left \frac{H_1}{W_1+2W_2} \sin(\beta) \right $		$el_{12} = \arctan \left \frac{H_2}{W_2+2W_1} \sin(\beta) \right $	

Table 1. Critical elevation angles [6]

Nb of reflections	Left side	Right side
0	$m_0 = 0$	
1	$m_1 = 2W_2 \cos(el) \sin(\beta)$	$m_1 = 2W_1 \cos(el) \sin(\beta)$
2	$m_2 = 2(W_1 + W_2) \cos(el) \sin(\beta)$	

Table 2. Corresponding additional distances [6]

3 Results and Comparisons

Nantes city centre is used as a test network, for the implementation of different cases, in the framework of this research. Experimental results obtained on 27th of February 2014 from 8:36 to 10:20 am, for a total duration of approximately 2 hours. Different GNSS observation data are used and evaluated, namely

¹ β denotes the angle difference between the satellite azimuth and the street direction, irrespective to the driving direction

GPS-only, GLONASS-only and GPS&GLONASS combination. Two methods are applied for the data processing. The first is the standard method, which uses ordinary least squares and considers all the satellites available per epoch to estimate user position. The other one is the 'Urban Trench' model, which introduces information of the street geometry by a 3D city model and corrects (if not removed) NLOS satellites.

The assessment of different constellations and methods is made in terms of accuracy and integrity. The results are compared with a 'ground truth' trajectory. In addition, fault detection and exclusion method is applied in order to compute the protection levels and enhance the accuracy of the output. The Stanford diagram is used to check and illustrate, in a clear way, the reliability of the final results.

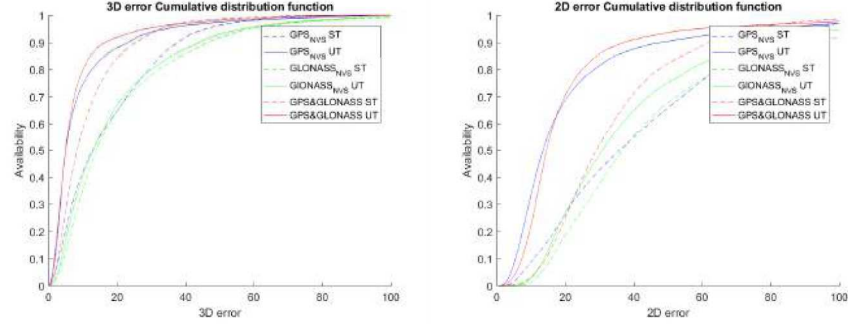
In particular, the results show that Fault Detection and Exclusion (FDE) benefits and improves the quality parameters, such as the accuracy and integrity of the user position solution. The recursive consistency-checking method is used to detect and exclude faulty data [7]. Several probabilities of false alarm (PFA) are checked to select the most appropriate for the test data. It is expected that the accuracy of the final positioning solution would be improved. Trials and error analysis show that a confidence interval of $\alpha = 0.01$ is suitable for the test data. The recursive consistency-checking method has a limitation. It is possible to eliminate wrong measurements in cases when multiple signals were affected by NLOS reception or strong multipath interference. Especially in urban canyons, signals come along the street direction and do not necessarily have a higher elevation than other signals.

Figures 3(a) and 3(b) aggregate all epochs. The cumulative 3D and horizontal error distributions are displayed, for the standard estimator and 'Urban Trench' model. The median error in both 3D and 2D has been reduced. While using the 'Urban Trench' model, there is an improvement globally. Comparing the different constellations and combination of them in terms of accuracy and integrity, one could conclude in the following ranking. For the NVS receiver, the relative results show that the dual-constellation combination has the best performance, GPS-only follows and last comes GLONASS-only. The latter case has the fewer satellites available per epoch and with low elevations. Probably, these are two reasons explaining GLONASS-only poor performance. However, it is derived from the results of GPS&GLONASS combination that GLONASS observation data contribute to the improvement of 3D positioning solution.

3.1 Overall Matrix

To sum up the results of the study, Tables 3 and 4 are created. The protection level is the usual integrity indicator of a localization algorithm [8]. Horizontal position errors are presented in Tables 3 and 4 because applications for ground transport are considered; the vertical dimension is not regarded. The different scenarios tested are the following:

- GPS_{ublox} without FDE implementation (GPSub-woFDE)



(a) 3D cumulative distribution function. (b) 2D cumulative distribution function.

Fig. 3. Cumulative distribution functions

- GPS_{ublox} with FDE and confidence intervals with $\alpha = 0.01$ (GPS_{ublox}-0.01)
- GPS_{NVS} with FDE and confidence intervals with $\alpha = 0.01$ (GPS-0.01)
- $GLONASS_{NVS}$ with FDE and confidence intervals with $\alpha = 0.01$ (GLO-0.01)
- $GPS\&GLONASS_{NVS}$ with FDE and confidence intervals with $\alpha = 0.01$ (GPS&GLO-0.01).

Respectively, the statistics that referred into Tables 3 and 4 are:

- 3D median position errors, in meters (m)
- 2D median position errors, in meters (m)
- Normal Operation (Norm Oper) for Horizontal protection level (HPL)
- Mis-leading information (MI) for Horizontal protection level (HPL)
- Mean number of satellites used (msat used) each epoch
- Mean number of satellites available (msat available) each epoch

Measurements have been discarded either due to outlier rejection based on statistics distributions (FDE) or geometry limitations corrections ('Urban Trench' model). Table 4 contains smaller values for all different cases, regarding the median errors and larger values concerning normal operation for integrity, trust of result. In particular, for example for GPS measurements, when 'Urban Trench' model is used the accuracy doubles, from 5.7 m median error, it drops to 3 m, while the integrity increases from 97% to 99.7%.

However, these integrity statistics derive from certain assumptions made through the research and their alteration could improve the Stanford diagram results. In particular, the probability of mis-detection (PMD) is set equal to 10^{-2} . From this value, the κ is derived, with four degrees of freedom (three for positioning and one for timing), $\kappa = 3.644$. With smaller PMD, the values of κ are larger, as it is for civil aviation, $PMD = 10^{-7}$ results in $\kappa = 6.18$.

Additionally, the standard deviation of the range measurements was fixed to $\sigma_R = 5$ meters. These parameters are used for the computation of protection levels and hence influence their values.

	Median error (m)		Integrity Statistics		Statistics	
	3D	2D	Norm Oper	MI	msat used	msat avail
GPSub-woFDE	17.5	5.7	97%	3%	7.3	7.3
GPSub-0.01	16.4	5.3	99%	1%	7.1	7.3
GPS-0.01	35.9	12.9	91%	9%	8.2	9.5
GLO-0.01	36.9	14.0	96%	4%	6.6	7.3
GPS&GLO-0.01	29.1	8.4	90%	10%	14.4	16.8

Table 3. Summary table for Standard Method.

	Median error (m)		Integrity Statistics		Statistics	
	3D	2D	Norm Oper	MI	<i>msat_{used}</i>	<i>msat_{avail}</i>
GPSub-woFDE	11.3	3.03	99.7%	0.3%	5.9	5.9
GPSub-0.01	11.3	3.0	99.97%	0.03%	4.9	5.9
GPS-0.01	13.5	5.0	99.4%	0.6%	6.1	6.3
GLO-0.01	30.9	13.0	98%	2%	5.8	6.2
GPS&GLO-0.01	14.6	5.0	99.95%	0.05%	8.7	8.9

Table 4. Summary table for 'Urban Trench' Method.

Also differences in the performance of the two different low-cost receivers can be found. Therefore, the quality of equipment (here NVS) is also critical for the accuracy and reliability of the outcome.

4 Conclusions

Examining each case, 'Urban Trench' method outperforms in comparison with standard method, both in terms of accuracy and integrity. The 'Urban Trench' approach is of great interest compared to using all satellites with no correction at all, or when only recursive consistency checking test is applied. It is an approximate geometric model and can compute in a deterministic way an accurate position by sorting and correcting the pseudo-ranges subject multipath with 1 or several reflections.

The number of available satellites is a major parameter of the improved GNSS performance. Accuracy can be maximised by selecting only those signals least contaminated by multipath and NLOS propagation to form the navigation solution and discarding the rest. Dual-constellation position solutions show an improved accuracy and reliability. Thus, performance might get higher as the number of GNSS satellites increases.

In conclusion, 'Urban Trench' model in combination with fault detection and exclusion test applied in multi-constellation observation data is a pretty efficient technique in terms of accuracy and reliability. However, this method trades availability for integrity, as data are removed, when not passing the tests.

In a future navigation application, signal reception at multiple candidate positions must be considered, which is more challenging. Thus, it is recommended, in [6], to implement the 'Urban Trench' model while the street is dividing into multiple driving lanes and examine the projection of initial solution into multiple hypotheses in parallel. If the rover was a pedestrian and not a car, side-walks

should be envisaged also as possible hypotheses. This method is expected to outperform conventional positioning in availability and positioning accuracy.

Finally, another future implementation and extension of this technique would be to resolve Low-cost Real-Time-Kinematic GNSS in exploitation of Cooperative ITS. Standard Real-Time-Kinematic GNSS systems are capable of centimetre accuracy, but combine high cost and poor robustness. It is a challenge to adapt 'Urban Trench' model to ITS (Intelligent Transport Systems) needs. Many Cooperative ITS applications, as collision avoidance, payment applications (e.g., road tolling, congestion charging, pay-as-you-drive services), require high accurate and reliable positioning, but at low cost, acceptable for the automotive industry [9]. The incorporation of digital spatial data might contribute to faster and more reliable positioning estimations.

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