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Weighting models for GPS Pseudorange observations for land transportation in urban canyons

Sarab Tay

Univ Lille Nord de France, F-59000 Lille,
IFSTTAR, LEOST,
F59650, Villeneuve d'Ascq, France
sarab.tay@ifsttar.fr

Juliette Marais

Univ Lille Nord de France, F-59000 Lille,
IFSTTAR, LEOST,
F59650, Villeneuve d'Ascq, France
juliette.marais@ifsttar.fr

Abstract—This paper addresses the problem of position computation in an urban canyon, using signals transmitted by Global Navigation Satellite Systems (GNSS) satellites. Due to the high masking level of buildings in a dense urban environment, the signals arrive at the receiver antenna often by more than one path (multipath).

Multipath is a source of positioning error, since the receiver solutions for position fail to converge, because of the travel time of the received signal and the moving vehicle.

In this paper, we are presenting a post-processing treatments based on observations variances modelling, in order to solve for vehicle position in an urban canyon.

Keywords—GNSS signal propagation, urban canyons, multipath, state of reception, weighting models, carrier-to-noise ratio, elevation angle.

I. INTRODUCTION

Localization systems are part of the improvement and attractivity efforts for better collective transportation systems. GNSS signals are widely used because this localization solution does not require to enhance the number and thereby the cost of investment and infrastructure. However, localization service quality is strongly degraded in urban environments where the signals are highly affected by diverse types of obstacles located around the receiver antenna. Signals are then subject to multipaths which decrease the accuracy of positioning. Moreover the EGNOS services devoted to increase accuracy by transmitting complementary signals by geostationary satellites suffer here from masking phenomena which make them unavailable. One of the solutions is to reduce the degradations and improve accuracy, it is explored in the COSYS/LEOST team. It consists in estimating a priori the conditions of signal reception.

In this paper, we will present some weighting models based on the GNSS received signals parameters, such as the satellite elevation and the signal strength in terms of the carrier to noise ratio (C/No), along with and the signals' state of reception in an urban canyon.

II. URBAN CANYON ENVIRONMENT

Four satellites at least are necessary to compute a GNSS position. A time of arrival is extracted from each received signal that corresponds to the satellite-to-receiver distance. As summarized in eq. 1, the pseudorange measurement is mainly affected by the propagation through the atmosphere and the environment around antenna :

$$\rho_{t,m}^s = d_t^s - c(\delta t^s - \delta t^u) + (I_t^s + T_t^s) + \epsilon_t, \quad (1)$$

where :

- d_t^s is the euclidian distance between the satellite s and the user at time t ,
- δt^s and δt^u are respectively the offset between the GPS system time and the receiver clock, and the offset between the GPS system time and the receiver clock,
- I_t^s and T_t^s are the ionospheric and the tropospheric errors,
- $\epsilon_t = m_t^s + w_t$ are the observations errors, with m_t is the error due to signal multipath, and w_t is the receiver noise.

The ionospheric and tropospheric errors can be modeled such in [1], whereas the poor satellite geometry and site environment antenna are difficult to treat.

In urban canyons, the presence of buildings of different heights, structures, and materials, dense vegetation, and street elements reduces highly the number of visible satellites and increases the presence of multipath.

Received signals may be classified into three types:

- Line-of-sight (LOS) signals (direct),
- Non Line-of-sight (NLOS) signals (reflected),
- Blocked signals.

Several techniques have been developed for multipath mitigation, for instance the Narrow Spacing Correlator [2], Multipath estimation Delay-Locked-Loop algorithm (MEDLL) [3], some Bayesian approaches [4] and array antenna algorithms [5]. Other solutions such as in [6] and [7] are made to exclude all the NLOS received signals. However, in [6] it was proved that a simple exclusion decreases the accuracy of user position in an urban area.

III. OBSERVATION WEIGHTING MODELS

In order to improve user position computation accuracy, we are using all received signals, jointly with the information on the state of reception.

Concretely, we propose a weighting model depending on the

quality of the signals and the geometrical form of the surrounding antenna environment. The strength quality of the signal is defined by the Carrier-to-Noise Ratio C/No, which is the ratio if the power level of the signal in 1 Hz bandwidth. The geometrical form of the city canyon defines the masking level of surrounding buildings. This affects directly signals transmitted from a low elevation angle.

Thus, C/No and elevation angles values, as recorded by the receiver, are used to model the pseudorange observations noise variance.

Further information about the geometrical form of the canyon for a defined vehicle path allow us to determine, epoch by epoch, if the signals are received within multipath or not. This information provided from the Caploc Project [8] will be used to introduce the our weighting model. Before presenting these models, let us remember some GNSS signal basis about user position computation.

The pseudorange observations equation can be written :

$$\Delta\rho = H\Delta X + \epsilon \quad (2)$$

H is the design matrix of the unit-vectors pointing from the linearization point to the location of the i -th satellite, and ΔX is the vector offset of the user's true position and time bias from the values at linearization point [9].

These observations are uncorrelated, and the errors are assumed to be normally distributed according to $\epsilon \sim \mathcal{N}(0, \Sigma)$. The inverse of the covariance matrix Σ will be used as the weighting matrix W , with the assumption that $H^T \Sigma^{-1} H$ is non-singular. The weighted least squares solution is :

$$\Delta\hat{X} = (H^T \Sigma^{-1} H)^{-1} \times H^T \Sigma^{-1} \Delta\rho, \quad (3)$$

The matrix Σ is a diagonal matrix, where the diagonal elements are constituted of the rms of the σ^2 , for a specified model. Whatever the used model, the geometric and position DOP can be calculated using the expression $(H^T \Sigma^{-1} H)^{-1}$.

We can find in literature some weighting models like the sigma- ϵ [10], sigma- Δ [11] and exponential model [12]. These models link the C/No to the variance of the pseudorange measurements errors by means of some specified parameters.

A. Sigma- ϵ and elevation model

Concretly, the sigma- ϵ model uses the CNo values of the GPS signals to estimate weights for least square adjustment [10]. Langley [13] has derived a formula that expresses the phase variance σ^2 as a function of the recorded C/No values. This formula was used for geodetic receiver. Wieser [14] has proposed a completed formula that goes with all receiver types :

$$\sigma_{se}^2 = v_i + c_i \cdot 10^{-0.1 \times CNo_{measured}} \quad (4)$$

where v_i (m^2) and c_i ($m^2 Hz$) are model parameters and i is the frequency index (L_1 or L_2).

As in [10], one should notice that the function $1/\sin^2(\theta_i)$ (θ_i is the elevation angle of the satellite) can be a good estimate for the error variance and weighting function. The weights increase with the elevation angle.

These two models present some lacks in a strong multipath environment. Actually, in the sigma- ϵ model, the variance σ_{se}^2 does not change with the signal being LOS or NLOS, it changes only with C/No changing. On the other hand, the elevation model is not always beneficial for low elevation angles (multipath). For instance we can find a very low satellite with a relatively high C/No (fig. 1).

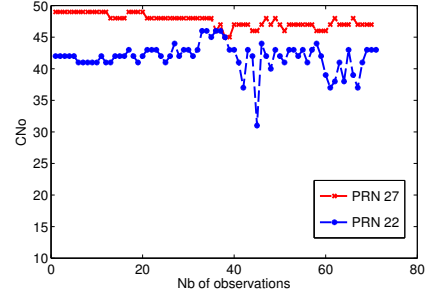


Figure 1. C/No values for PRNs 22 (elev. angle ≈ 17 deg.) and 27 (elev. angle ≈ 70 deg.)

That is why we have developed a complete model that consider both C/No and the elevation angle of a received signal at the same time. In this model, the variance σ_{sr}^2 is changing with the elevation angle of the received signal and its carrier-to-noise density power. Since variance increases with multipath, this ratio is then multiplied by a coefficient k , k is determined whether the signal is LOS or NLOS.

The state of reception of the received signal can be determined as in the Caploc Project, presented in the next paragraph.

B. C/No - Elevation model : Image analysis contribution

The Caploc project proposes a solution based on combining the image analysis and knowledge about the signal propagation for localization applications. The aim of this project is to classify, in a deterministic way, the received signals depending on the state of reception.

The system developed in this project uses a camera with a fisheye lens. During the acquisition campaign, the camera records images of the surrounding environment. The pixels of the recorded images are classified into two zones : sky and non-sky (fig. 2) and (fig. 3).

This classification permits to detect the mask caused by the buildings and other elements (fig. 2), and therefore to determine the position of the satellites in this sky map (fig. 3). The sky zone denotes the LOS received signals, while in the non-sky zone, signals are supposed to be received after one or many reflections.

The variance of the C/No - Elevation model is :

$$\sigma_{sr}^2 = k \times \frac{10^{(-0.1 \times CNo_{measured})}}{\sin^2(\theta_i)} \quad (5)$$

When the received signal is LOS, k is supposed equal to 1. Whereas, when it is NLOS, k changes. In this paper we have computed the weights $w_{sr} = 1/\sigma_{sr}^2$ for $k = 1, 2$ and $k = +\infty$.

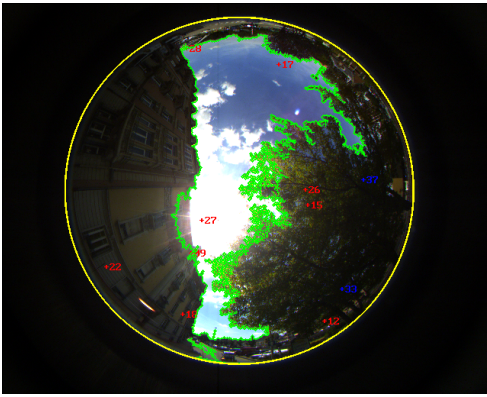


Figure 2. Fish-eye camera image : detection of objects and vegetation edges [15]

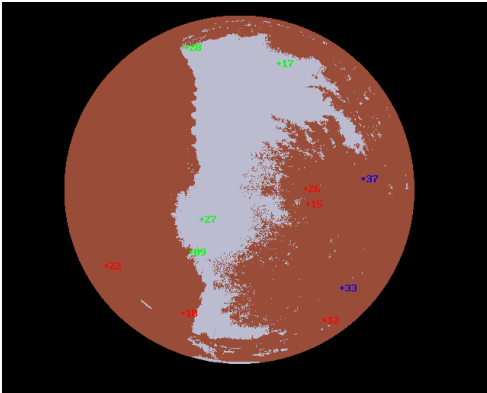


Figure 3. Fish-eye camera image : classification of the image pixels into Sky/Non-Sky zones. Different state of reception satellites are also presented (Green = LOS), (Red = NLOS) and (Blue = Blocked)

IV. MEASUREMENTS CAMPAIGN AND FIRST RESULTS

To validate the proposed algorithms, we have used measurements realized on June 2010 in the city of Belfort, France. Data acquisition was performed with a 1 Hz frequency Septentrio receiver for the NMEA data and 27 Hz for the camera. The path we are using here has a duration of about 71 GPS positions for Septentrio and 171 points for the RTK system.

For illustration, fig. 4 shows the RTK trajectory, along with GPS positions computed with our C/No - elevation model (CE model), elevation model and ordinary least squares method. This figure shows a good improvement of the vehicle position computation when the CE model is used.

The figure 5 shows the vehicle position errors with respect to the RTK trajectory. Positions computed with the CE model ($k = 2$) present a very low error level. In table I, we have drawn the standard deviation (σ) and the root mean square errors values for all methods. We can see that there is a deviation improvement of 76.89% and RMS improvement of 72%.

Table I. STANDARD DEVIATION AND RMS ERROR VALUES FOR THE THREE MODELS, WITH $k = 2$

	OLS	CNo / Elevation	Elevation only
Std deviation (m)	10.82	2.5	8.24
RMS(m)	15.074	4.11	11.86

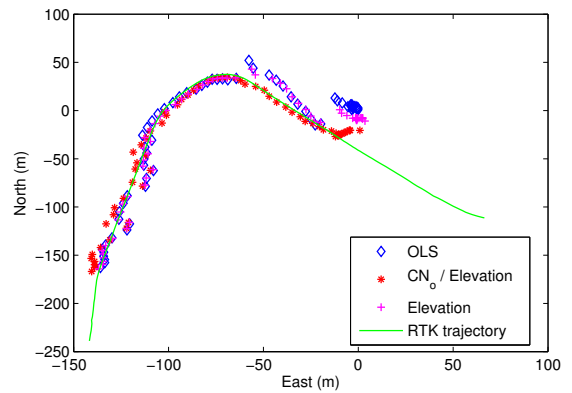


Figure 4. Reference trajectory RTK, CE model, elevation model and OLS vehicle position.

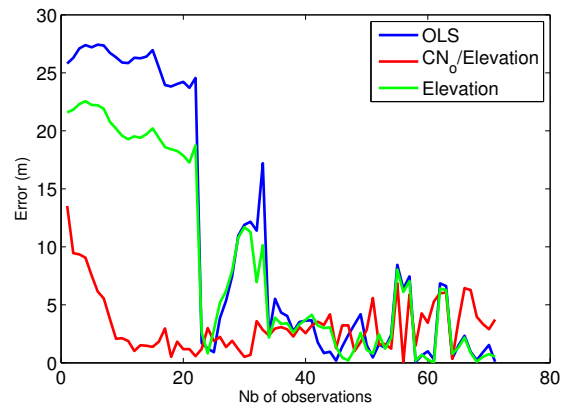


Figure 5. Position errors (all models) with respect to the RTK trajectory, $k = 2$

When $k = 1$, a good position is obtained also (table II), but it still less important that $k = 2$.

We have also tried the solution about excluding the NLOS signals by using the CE method with $k = +\infty$. This means that the variance σ_{sr}^2 is infinite and the weights w_{sr} are equal to zero. Thereby, NLOS signals are excluded from position computation.

When only methods excluding GPS, such as OLS or CE model ($k = +\infty$) are used, the position accuracy is highly degraded. Actually, as we can see in fig. 7, the acquisition zone constitutes a typical urban canyon with high and large buildings, dense vegetation, cross streets, ...

The yellow spot in this same figure indicates the map zone where NLOS are highly present. These multipath result in the outliers observed in fig. 6 (observations [0 : 23]) and fig. 4 (East [-20m : 20m]).

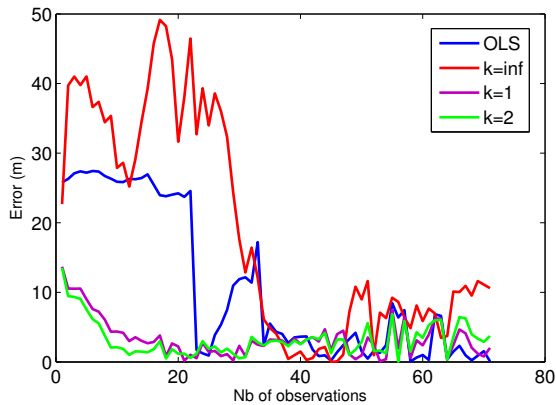
Our CE model including NLOS signals presents a very good solution for multipath problem in an urban canyon. On the same figures above, position accuracy is clearly improved when the CE model is used, even in the outliers zone.

V. CONCLUSION

The aim of our work is to develop a weighting model able to solve for multipath problem in an urban canyon

Table II. STANDARD DEVIATION AND RMS ERROR VALUES FOR THE THREE MODELS, WITH $k = 1$

	OLS	CNo / Elevation	Elevation only
Std deviation (m)	10.82	2.76	8.24
RMS (m)	15.074	4.4	11.86

Figure 6. Comparison of position errors for some given values of k .Table III. STANDARD DEVIATION AND RMS ERROR VALUES FOR THE THREE MODELS, WITH $k = +\infty$

	OLS(m)	CNo / Elevation	Elevation only
Std deviation (m)	10.82	15.74	8.24
RMS	15.074	24.4	11.86

environment.

In this paper, we have presented the CE weighting model which uses data about both carrier-to-noise density power of the received signal and its elevation angle.

An image classification algorithm permitted us to decide if the received signal is LOS or NLOS. The CE model is then applied with a scalar (k) that changes according to the signal type.

The first results are very promoting, since we have noticed an improvement of 76.89% on the standard deviation value between the CE weighting model and OLS method.

In order to validate this model, we believe that it should be applied in other urban environments with strong multipath profiles. We have already performed another measurement campaign in a very dense district of Lille. On the other hand, it would be interesting to compare the performances of kalman filter and CE model in the same environment conditions, and to implement real-time processors to compute vehicle position.

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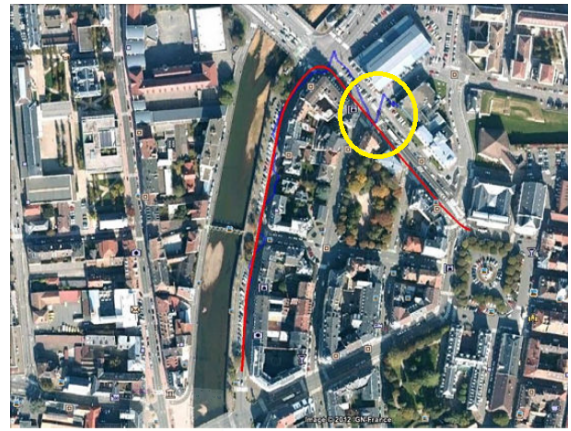


Figure 7. Part of Belfort city where GPS signal acquisitions were performed.

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