Characterization of Carrier Phase Measurement Quality in Urban Environments

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Lina Deambrogio, Olivier Julien
Ecole Nationale de l'Aviation Civile
(ENAC)
Toulouse, France
Email : deambrogio@recherche.enac.fr; ojulien@recherche.enac.fr

***Abstract*—The feasibility of precise positioning techniques in urban scenarios is dependent on the quality of carrier phase measurements. Given the lack of robustness of carrier phase tracking and its limitations in constrained scenarios, it is hence important to be able to characterize carrier phase measurement quality and define guidelines for measurement selection prior to computing the receiver position. In this paper, an analysis of optimal tracking settings is carried out and phase measurement quality is investigated by considering the effects of multipath in an exemplary urban scenario.**

Keywords—Carrier phase; Tracking; Multipath; DLR multipath model; Mask angles

I. INTRODUCTION

Carrier-phase tracking is an important operation in a GNSS receiver since it allows data demodulation but also because it can provide very precise, although ambiguous, pseudorange measurements to the navigation processor. Carrier-phase-based measurements can in fact be used to improve the positioning solution either through their direct use in the position computation or by filtering the less accurate code measurements.

However, carrier phase tracking is also well-known as being one of the weakest stages in a GNSS receiver due to its lack of robustness in environments where fading and high dynamics cause sudden changes in the signal parameters. In order to overcome this drawback, most of the current GPS receivers destined to work in urban environment can rely to track the carrier frequency on the use of a FLL, which is more robust but less accurate than carrier-phase tracking, and/or using external links to get the navigation message.

It is quite clear, however, that the ability for the receiver to use the precise carrier-phase measurement would provide a strong advantage since it could significantly improve the positioning accuracy of the receiver, even in difficult environments. This feature could clearly be a strong differentiator from present mass-market receivers.

In this context, in order to evaluate the feasibility of carrier phase positioning techniques in urban environments, two different axes should be considered: signal processing, in order to improve the quality of the carrier phase tracking and deliver healthy measurements, and measurement processing, to filter and select the measurements that will be used for position computation. It is then important as a first step to consider carefully the choice of suitable tracking loop settings to provide optimal tracking performance in an urban scenario without impacting on receiver complexity. To this end it is important to identify the tracking settings through the theoretical analysis of the Phase Lock Loop (PLL) tracking sensitivity as a function of the PLL loop bandwidth and integration time [1].

The second step is to analyze the quality of carrier phase measurements in a typical urban scenario in order to obtain a characterization of their quality and deduce guidelines for their selection. In fact, by determining a possible mask for the satellite angles and received signal-power-to-noise-density-ratio C/N_0 it can be possible to exclude from the precise positioning algorithm highly deteriorated measurements.

To test as extensively and accurately as possible the effect of multipath, a specific receiver platform, referred to as GeneIQ, was developed. This platform is based on the concept of semi-analytic receiver simulators, meaning that the receiver simulator is built based on the accurate modeling of correlator outputs.

Simulations have been carried out by employing signals which have been modified by the effects of the DLR Land Mobile Satellite (LMS) Channel Model [2] [3] and injecting them in the GeneIQ simulator.

The characterization of carrier phase measurement quality has been conducted considering the impact of multipath on the tracking stage in terms of tracking error but also of PLL loss of lock [4].

II. SELECTION OF TRACKING SETTINGS

In general, the decision on the choice of the PLL settings (loop bandwidth, correlation duration, discriminator, etc.) is based on the computation of the PLL tracking threshold. A conservative rule of thumb is that the 3-sigma jitter must not exceed half of the phase pull-in range of the PLL discriminator. The typical criterion to assess this threshold is given by [1] as:

$$3\sigma_{\varphi} + \theta_e \leq \frac{L_{\varphi}}{2} \tag{1}$$

where:

- $\sigma_{\varphi} = \sqrt{\sigma_t^2 + \sigma_{Vib}^2 + \sigma_{Osc}^2}$ is the total phase tracking error standard deviation
- σ_t^2 is the variance due to thermal noise

- σ^2_{Vib} is the variance of the phase tracking error due to the oscillator vibrations
- σ^2_{Osc} is the variance of the phase tracking error due to the oscillator phase noise
- θ_e is the phase tracking bias due to a signal dynamics
- L_φ is the two-sided discriminator linear tracking region

The justification behind (1) is that the tracking error should remain within the carrier phase discriminator linear range in order for the loop to have a normal behavior and for the tracking to be feasible.

For a data signal and a pilot signal, different types of discriminators can be selected allowing achieving different performance. For data signals, the discriminator needs to be chosen so as to be insensitive to data bit transitions [5]. The most widely used discriminator is in this case the Dot Product (DP), which is expressed as the product between in-phase I_P and quadra-phase Q_P prompt correlation components:

$$D_{DP} = I_P Q_P \tag{2}$$

The linear tracking region of this discriminator is $L_\varphi = [-\pi/4; \pi/4]rad$ [1][5].

On the other hand, for pilot signals, there is no longer the need to be robust against bit transitions and the coherent discriminator can be used:

$$D_{Coh} = Q_P \tag{3}$$

The stability domain of the coherent discriminator is twice as large as for the DP phase discriminator as it tracks the phase error directly yielding $L_\varphi = [-\pi/2; \pi/2]$ [1]. Both presented data and pilot phase discriminators require a normalization to remove the impact of the signal power.

Having defined the tracking threshold, it is then possible to identify the optimal loop bandwidth and integration time for given maximum signal dynamics, oscillator phase noise and thermal noise, by considering the impact of each error against the threshold.

The presence of thermal noise creates a tracking error that can be expressed for data and pilot signals respectively as [1][6][7][8]:

$$\sigma^2_{t,data} = \frac{B_L^{PLL}}{\frac{C}{N_0}}\left(1 + \frac{1}{2\frac{C}{N_0}T_I}\right)(rad^2) \tag{4}$$

$$\sigma^2_{t,pilot} = \frac{B_L^{PLL}}{\frac{C}{N_0}}(rad^2) \tag{5}$$

With B_L^{PLL} defining the loop bandwidth in Hz, C/N_0 the carrier to noise power density ratio in dBHz and T_I is the coherent integration time in s. It should be noted that in the case of a pilot signal, a degradation of 3dB should be considered when processing only the pilot signal. As evidenced by (4) and (5), the tracking error variance due to thermal noise can be limited by reducing the equivalent loop bandwidth or extending the integration time. In Fig. 1, the effect of the loop bandwidth on the PLL phase jitter is exemplified for a data signal and fixed integration time T_I=20 ms, showing that in order to limit the effect of noise, smaller bandwidth should be considered.

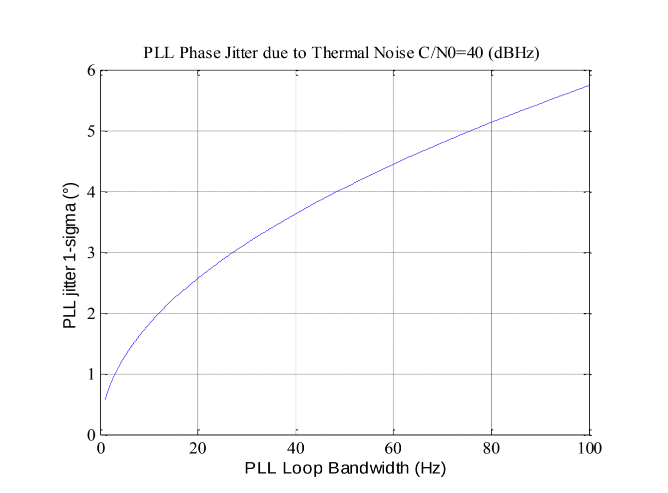

Fig. 1 PLL Thermal noise jitter vs PLL loop bandwidth

Conversely, receiver oscillator phase noise, vibrations and signal dynamics can all be modelled as having analogous effects: they are perceived by the receiver as creating delay and phase variations that translate in an additive term in the instantaneous incoming signal Doppler. As a consequence, the PLL has to track also this additional phase variation in order not to lose lock, requiring the PLL to react very fast to phase variations (caused by low quality oscillators or high dynamics). The PLL loop bandwidth has then to be quite large or equivalently the correlation time needs to be fairly small in order to have a limited phase variation during the correlation operation. The computation of σ_{Vib}, σ_{Osc} and θ_e can be obtained following [9] and [10].

It is then clear that a trade-off needs to be reached between robustness against thermal noise and reactiveness to changes in the received signal due to dynamics and oscillator instabilities.

For a third order PLL, given a fixed integration time T_I=20 ms and C/N_0= 40dBHz, a TCXO oscillator with parameters h_2=2e-20 (1/s), h_1=1e-20, h_0= 1e-21(s), assuming constant values for the oscillator g-sensitivity ($k_g(f) = k_g$=1e-9 (1/g)) and power spectral density ($G_g(f) = G_g$ = 0.05 (g^2/Hz)) [9] and maximum dynamics characterized by jerk=1 (g/s) it is possible to obtain the behaviors reported in Fig. 1 and Fig. 2 for the different error contributions and the total error.

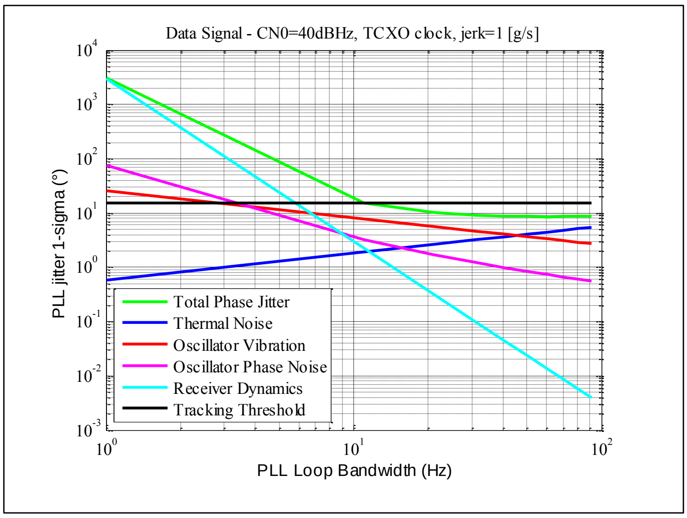

Fig. 2. PLL phase jitter contributions and Threshold for a Dot Product tracking loop

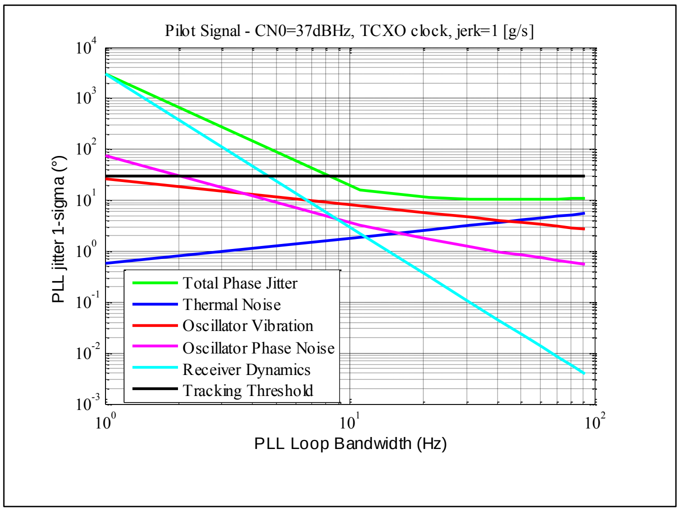

Fig. 3. PLL phase jitter contributions and Threshold for a Coherent tracking loop

Fig. 1 and Fig. 2 show the individual phase jitter contributions and the total phase jitter against the tracking threshold. Consequently, it is intuitive to determine the range of possible bandwidth that can be selected to allow tracking as the bandwidths that guarantee that the total error is below the tracking threshold.

In urban environments, also the effect of multipath should be taken into account. To this end, it is then important to notice that multipath components have an inherent phase variation that distinguishes them in the frequency domain from the Line Of Sight (LOS), allowing filtering the multipath out and concentrating only on the LOS. This filter can be realized either by selecting a very narrow loop bandwidth or by extending the correlation time, obtaining a low pass filter that attenuates multipath with a Doppler component differing from the Doppler of the local replica.

Among the bandwidths identified through the sensitivity analysis carried out above without including multipath and considering a standard integration time of 20ms, the lowest possible value of bandwidth should be chosen as the one better suited for rejecting the impact of multipath.

As a conclusion:

- the GPS L1 C/A PLL should use a Dot Product and a loop bandwidth as narrow as possible comprised within [15; 20] Hz;
- the Galileo E1 OS PLL could use either the coherent and a loop bandwidth as narrow as possible comprised between 10 and 15 Hz.

III. Scenario Description

The DLR Land Mobile Satellite (LMS) Channel Model [2] [3] has been used to simulate an urban environment consisting of a user moving with constant velocity along a street surrounded by buildings, trees, and lampposts that can hinder the reception of the signal transmitted by a satellite with fixed elevation and azimuth angles. This model has been used to obtain the delays, amplitudes and phase shifts of the LOS and reflected path signals. A combination of a deterministic and a statistic approaches is considered in the model: obstacles are placed and shaped following a Gaussian distribution. Once placed, however, they present a deterministic behavior.

The direct path component is determined by physical deterministic effects generated by house fronts, trees and lampposts. House front diffraction is modeled as a knife edge model, tree attenuation is modeled as proportional to the path length through the tree canopy plus a stochastic fading process and lampposts are modeled through a double knife edge model. The multipath signals are caused by reflectors that are generated following statistical data obtained through a measurement campaign carried out by DLR.

A typical urban scenario has been tested considering:

- A vehicular user moving with constant velocity along the street;
- The street is assumed to be 15 meters wide;
- The size of the buildings follow a Gaussian distribution with the width $W_B \sim N(22m, 25m)$ with $W_B \geq 10m$ and the height $H_B \sim N(17m, 6.4m)$ with $8 \leq H_B \leq 50m$;
- The gap between buildings appears with probability $p_G = 0.18$ and a gap width $W_G \sim N(27m, 25m)$ with $W_G \geq 10m$;
- Trees have a constant height of 8 m and a diameter of 5 m. Tree trunks have a constant length of 2 m a diameter of 0.2 m. Leafs are assumed to cause an attenuation of 1.1 dB/m. The distance between the trees and the buildings is 2 m. The distance between trees follows a normal distribution $d_T \sim N(20m, 2m)$ with $d_T \geq 1m$;
- Lampposts have a constant height of 8 m and a diameter of 0.2 m. The distance between lampposts follows a normal distribution $d_L \sim N(10m, 2m)$ with $d_L \geq 1m$;

- Reflected signals are considered up to a maximum attenuation of -45 dB

To assess the robustness of the carrier phase tracking block to multipath and fading, a database of received rays has been processed. The database contains the time series of received rays from a satellite at different positions generated with the DLR LMS. The elevation angles considered are comprised within [10°- 80°] with 10° steps and the azimuth angles are within the range [0° - 90°] with 45° steps, considering the street axis as azimuth 0°. Simulations of 20s duration have been performed for each satellite's azimuth and elevation angle pair. The number and length of the simulations has been chosen according to criteria of computation time, output data size and accuracy of the model. Moreover, considering a receiver moving along the street (azimuth angle of 0°) at 50 km/h speed, the considered sampling rate for the DLR model has been set to 1 KHz as reported in Table 1[11]:

$$T_s = \lambda/(8\,v) \tag{6}$$

Where:

- λ is the signal wavelength (m)
- v is the receiver velocity (m/s)

TABLE 1 SAMPLING INTERVALS

		Frequency Band			
		L1/E1	***L5***	***E5a***	***E5b***
Velocity (km/h)	50	1.7 ms	2.3 ms	2.3 ms	2.2 ms
	90	0.95 ms	1.3 ms	1.3 ms	1.2 ms

IV. SIMULATOR DESCRIPTION

In order to test as extensively and accurately as possible the proposed algorithms, a specific receiver platform, referred to as GeneIQ, was consolidated. This platform is based on the concept of semi-analytic receiver simulators, meaning that the receiver simulator is built based on the accurate modeling of correlator outputs. Being able to model accurately correlator outputs means that the correlation operation, the most demanding in a GNSS receiver, does not need to be performed, saving a lot of simulation time. The correlator output model for a data component is given by:

$$\mathrm{I}(k) = \frac{A}{2} d\big((k+1)T_I\big) R(\varepsilon_\tau)\,\mathrm{sinc}\big(\pi\varepsilon_f T_I\big)\cos\big(\varepsilon_{\theta_0}\big) + n_i(k) \tag{7}$$

$$\mathrm{Q}(k) = \frac{A}{2} d\big((k+1)T_I\big) R(\varepsilon_\tau)\,\mathrm{sinc}\big(\pi\varepsilon_f T_I\big)\sin\big(\varepsilon_{\theta_0}\big) + n_q(k) \tag{8}$$

Where:

- A is the incoming signal amplitude
- R is the correlation function between the incoming PRN including its modulation and the local replica
- T_I is the correlation duration
- d is the data bit value, or secondary code value during the integration interval
- ε_τ is the time shift between the incoming and local PRN codes
- ε_f is the frequency shift between the incoming and local carriers
- ε_{θ_0} represents the phase difference between the incoming and local carrier in the middle of the correlation interval
- n_i and n_q are the in-phase and quadrature phase correlator output noise components due to thermal noise. These noise components are independent and follow a Gaussian distribution with a power equal to $\frac{\mathrm{N_0}}{4\mathrm{T_I}}$

Such a model is valid as long as the amplitude and frequency of the incoming signal remain constant during the correlation interval. This hypothesis is generally fulfilled for correlation duration on the order of a millisecond, which is the case for GNSS. However, these assumptions should be tested whenever the propagation channel is expected to have high frequency components (fast changing parameters) as it could be the case for an urban environment.

Because the correlator output rate is in the order of the kHz, it is easy to understand that the simulation duration will be much lower than when simulating the true received signal with a sampling frequency on the order of a few MHz. It is thus an interesting tool to have a first performance analysis of specific techniques.

Based on (7) and (8) it is then possible to model most of the degradations affecting the correlator output used to track the signal:

- signal strength (based on an adapted link budget)
- signal modulation (by modifying the shape of the correlation function)
- RF front-end filtering (by modifying the shape of the resulting correlation function)
- signal dynamics (such as receiver motion, satellite motion, atmosphere variation)
- receiver clock phase noise (by accurately modeling the clock phase noise coming from the receiver clock, as performed in [9])
- thermal noise (by adding a noise term with the correct variance to the correlator output model)
- multipath (by summing as many correlator outputs as there are multi-paths, given that the amplitude, delay and phase of the multipath are known and that the Doppler associated with the multipath is constant over the correlation duration)

- RF interfering (either as a reduction of the C/N0, or as a specific model in case of a CW)

Following the accurate modeling of the correlator output, it is then possible to implement tracking loops and to output measurements such as code, phase and Doppler measurements. In order to assess the robustness of the carrier phase tracking block to multipath and fading, the database of received signal rays has been processed with a similar approach to [12] within the GeneIQ module to provide the tracking errors and additional data like the percentage of lock.

V. MEASUREMENT QUALITY ANALYSIS

In order to use carrier phase measurements for precise positioning, it is finally important to address the issue of measurement quality. Indeed, in urban scenarios, the presence of multipath and fading can severely impact the feasibility of precise positioning techniques by degrading the quality of carrier phase measurements and by limiting their availability.

In the following three different metrics have been applied for characterizing carrier phase measurement quality:

- Tracking error standard deviation, to describe measurement accuracy;
- Number of cycle slips, identifying discontinuity of the measured carrier phase resulting from a temporary loss of lock in the carrier tracking loop of a GNSS receiver that requires re-initializing the ambiguity estimation block in order to avoid erroneous results in high precision solutions [13];
- Percentage of successful tracking, defining the availability of the measurements.

Tracking is locked according to the phase lock detector [4]. The detector is based on the concept that, if the incoming signal is being correctly tracked, then the in-phase component of the prompt correlator I_P is maximum, and its quadrature component Q_P is minimum:

$$\cos(2\varepsilon_{\theta_0}) = \frac{[\sum_M I_P]^2 - [\sum_M Q_P]^2}{[\sum_M I_P]^2 + [\sum_M Q_P]^2} \qquad (9)$$

Where:

- ε_{θ_0} is the carrier phase;
- M is the number of coherent integrations.

In lock conditions $0.4 \leq \cos(2\varepsilon_{\theta_0}) \leq 1$. When lock is lost, then we suppose going to reacquisition.

The following results have been computed considering:

- A GPS L1 C/A signal
- DLL discriminator: EMLP with correlation duration: 20ms and B_L^{DLL}=1 Hz
- PLL discriminator: DP; PLL correlation duration: 20ms; B_L^{PLL}: 15 Hz. A loss of lock is counted when the lock detector value goes below a predefined threshold (0.4). If the PLL breaks lock, the carrier tracking falls back to reacquisition.
- TCXO oscillator with parameters h_2=2e-20 (1/s), h_1=1e-20, h_0= 1e-21(s)
- Maximum dynamics with jerk=1 g/s
- Azimuth angle=90°

TABLE 2 CARRIER-PHASE TRACKING PERFORMANCE

		Std tracking error (rad)	*Cycle slip events*	*Tracking availability (%)*	*Mean Estimated C/N0 (dBHz)*
Elevation Angle (°)	***10***	0.80	1	11	4
	20	0.46	1	4.5	7
	30	0.51	12	20.5	9
	40	0.18	0	100	34
	50	0.14	0	100	36
	60	0.13	0	100	35
	70	0.13	0	100	35
	80	0.10	0	100	35

The results show that an elevation mask angle equal to 40° should be applied to guarantee tracking of the carrier phase and availability of the carrier phase measurement. Analogous results can be obtained for other azimuth angles.

In order to show in a clearer manner the behavior of the PLL in the presence of multipath, in the following the tracking error time series and estimated C/N_0 values are depicted for the worst case elevation angle 10° and for the mask angle case of 40°.

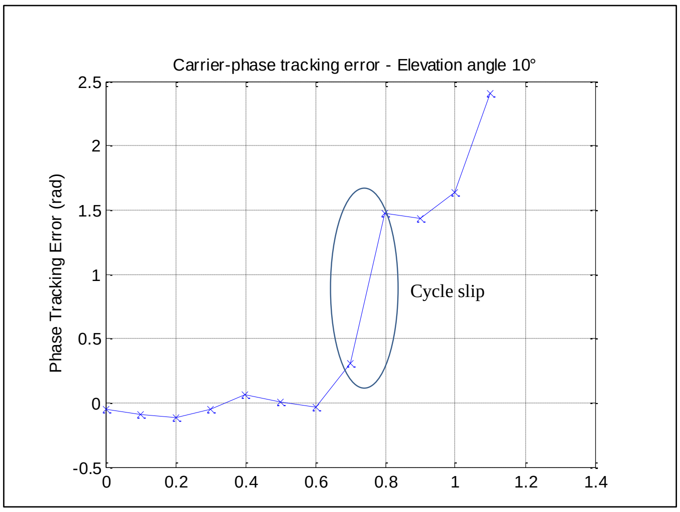

Fig. 4 Carrier phase tracking error time serie at elevation angle 10°

Only the epochs in which carrier phase tracking is available have been plotted. It is then clear that at low elevation angles tracking is impossible and performance are clearly degraded as can be seen from Fig. 5, reporting the estimated C/N_0.

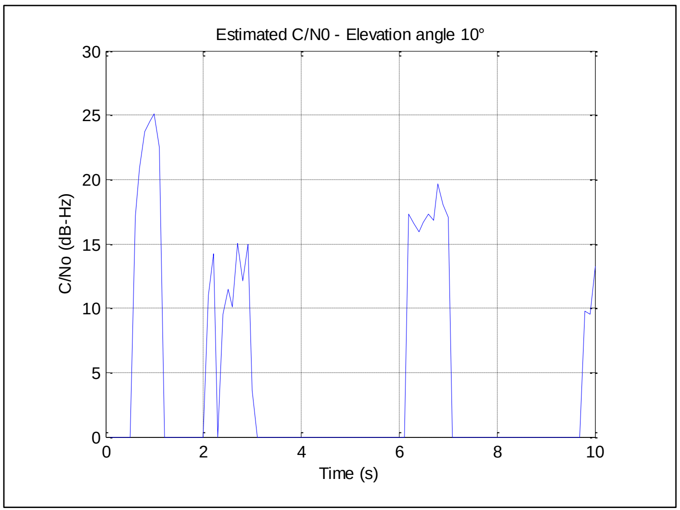

Fig. 5 Estimated C/N_0 for the elevation angle 10°

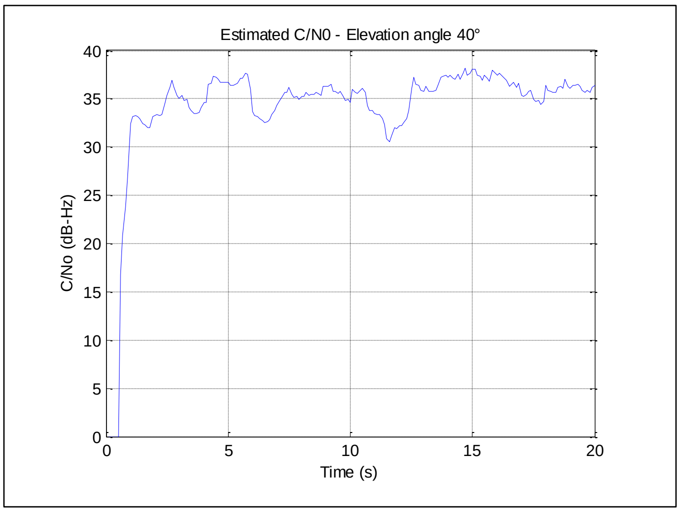

Fig. 7 Estimated C/N_0 for the elevation angle 40°

Conversely, has shown in Fig. 6 and Fig. 7, at 40° of elevation performance clearly improve suggesting both in terms of tracking error performance and estimated C/N_0.

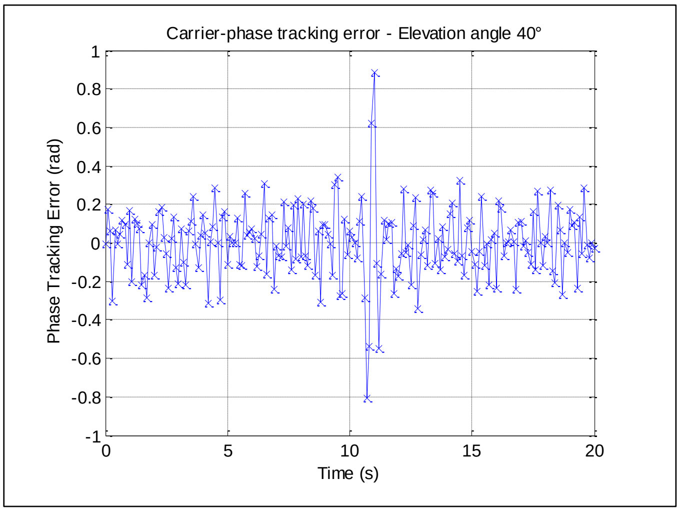

Fig. 6 Carrier phase tracking error time serie at elevation angle 40°

This analysis shows the vulnerability of the PLL in difficult environments. In this context, in order to use precise positioning techniques, it becomes thus fundamental to be able to increase carrier phase measurements availability and reduce the occurrence of cycle slips.

The analysis shows that a measurement selection should be carried out through the use of a mask angles. Simulations identify the elevation angle equal to 40° as a mask angle good.

VI. CONCLUSIONS

This paper has presented an analysis of carrier phase tracking in urban scenarios. The analysis has been carried out to identify tracking settings and a selection criterion for the carrier phase measurement. The analysis has shown that higher elevation angles generally yield better performance in terms of carrier tracking loss of lock events and has identified elevation angle equal to 40° as a good candidate for a masking angle. Other types of measurement selection could also be considered by using estimated C/N_0 masks. It should be noted that a selection of measurements can have an effect on the position by degrading the satellite geometry. However, with the availability of future constellations including GPS, GLONASS and Galileo, the low availability of measurements in urban areas should be less problematic.

ACKNOWLEDGMENT

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