Impact of multipath and cross-correlation on GPS acquisition in indoor environments

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BIOGRAPHY

Hanaa A. EL-NATOUR graduated from the Lebanese University of Beirut in 2002 (Engineering degree in Networks and Telecommunications), and from the ENSEEIHT in Toulouse, France in 2003 (masters of research degree in Networks and Telecommunications). Currently, she is a PhD student at the ENAC (Ecole Nationale de l'Aviation Civile), in Toulouse, France. She is investigating different signal processing techniques for indoor GPS positioning.

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Marie-Laure BOUCHERET graduated from the ENST Bretagne in 1985 (Engineering degree in Electrical Engineering) and from Telecom Paris in 1997 (PhD degree). She worked as an engineer in Alcatel Space from 1986 to 1991 then moved to ENST as an Associated Professor then a Professor. Her fields of interest are digital communications (modulation/coding, digital receivers, multicarrier communications …), satellite on-board processing (filter banks, DBFN …) and navigation systems.

ABSTRACT

The need for indoor localization is expected to increase dramatically with the rising Location-Based Services (LBS) and other location and navigation applications. But the challenging indoor environment is one of the biggest obstacles for indoor localization. The aim of the proposed paper is to analyze the performance of the L1 GPS signal acquisition in indoor environments, in the presence of multipath and of cross-correlation effects.

I. INTRODUCTION

In the past, in order for GPS to work accurately, the presence of an unobstructed Line-Of-Sight (LOS) signal was necessary. Weak signals were not suitable for use because they may have large associated noise and other errors. The expansion of GPS to Location-Based Services and other navigation applications all over the world, such as the E-911 and the E-112 mandates in the United States and Europe respectively, is changing the paradigm. Consequently a dramatic increase in the number of required indoor wireless systems is expected. These rising indoor localization requirements pose a particularly difficult challenge for system designers, since an indoor channel is highly complicated and path loss is very severe most of the time.

An indoor radio communication channel is governed by multiple factors like multipath propagation, shadowing effects, surrounding objects velocity, mobile relative velocity, and signal interference (either with other GPS signals or with other radio signals). The multipath consists of different replicas of the original signal caused by reflections, diffractions or diffusions generated when the signal encounters an obstacle. These replicas are attenuated versions of the original signal; they have different phases, and different arrival times. At the receiver they combine and produce a distorted version of the transmitted signal. The shadowing effect mainly attenuates the direct signal. This attenuation is very severe when the signal must pass through concrete walls, or dense foliage. On the other hand, the mobile relative velocity with respect to the emitting satellite makes the channel variable over time. Furthermore, signal interference with other radio signals and cross-correlation with other GPS signals also causes a signal distortion.

In order to design an indoor radio communication system with optimal performance, there must be a subtle study of the channel characteristics.

In this paper we mainly investigate the impact of multipath and cross-correlation on GPS L1 signal acquisition in a simulated typical indoor environment. For that purpose we have defined a time-varying mobile radio channel model, based on an indoor channel model realized within an ESA (European Space Agency) project entitled "Navigation signal measurement campaign for critical environments" and presented at the ION-GPS-2003 [F. Pérez-Fontán et al., 2003]. In this project, the ESA investigated a statistical non-time-varying model which provides the PDF (Probability Density Function) for each of the four parameters used to characterize the channel: the number of paths, each path's amplitude, delay, and phase. These parameters were set to be constant over time. In our model we generate an original signal which stands for a direct LOS signal, and many reflected and diffracted replicas of this signal. The difference between this model and that of the ESA is that each path delay and phase are assumed to be time-varying. For the sake of simplicity, the relative amplitudes and the number of paths are assumed to be constant during the acquisition period. These two parameters are chosen at the beginning of the simulation according to their respective distributions presented in the ESA paper.

This model is used to study the effect of either multipath or GPS signals cross-correlation on the acquisition phase of the signal processing in the receiver.

The paper is organized as follows: first we describe the indoor channel model used, next, we present the acquisition algorithm developed under Matlab®. The two subsequent parts show simulation results. The first shows the impact of multipath on the acquisition performance, while the second deals with interference induced by another GPS signal. Finally, a conclusion is drawn from these results.

II. THE INDOOR CHANNEL MODEL

The GPS signal studied is considered as the output of an indoor time-varying channel which has the following transfer function:

$$h(t)=\sum_{i=1}^{N}\alpha_i\cdot\delta\left(t-\tau_i(t)\right)\cdot e^{j\theta_i(t)}$$

Eq 1

Where

N is the number of rays that reach the receiver. This set of rays may either contain a direct LOS or not. N is constant over the duration of the simulation, and is chosen according to the distribution of the number of rays reaching the receiver given in [F. Pérez-Fontán et al., 2003],

α_i is the multipath replicas relative amplitude with respect to the amplitude of the direct ray. This parameter is considered to be constant over the duration of the simulation, and is also chosen according to the distribution of the rays powers given in [F. Pérez-Fontán et al., 2003],

τ_i is the delay experienced by the direct LOS ray and the reflected rays respectively. This delay is essentially due to the signal propagation from the satellite to the receiver,

$\theta_i(t)=2\pi f_0\tau_i(t)-\theta_{0i}$ is the phase distortion introduced by the channel. θ_{0i} is a random initial phase uniformly distributed over $[0;2\pi]$.

Consequently, the GPS signal that is supposed to reach the receiver has the following expression:

$$s(t)=\sum_{i=1}^{N}\alpha_i\cdot c\left(t-\tau_i(t)\right)\cdot d\left(t-\tau_i(t)\right)\cdot\cos\left(2\pi f_0 t-\theta_i(t)\right)$$

With L_1 the Coarse/Acquisition (C/A) GPS code carrier frequency, $L_1=1575.42MHz$, c the C/A code, and d the data bits.

When processing the GPS signal we assume that the carrier frequency was already shifted to an Intermediate Frequency (IF) of 1.25 *MHz*.

The studied signal is then:

$$s(t)=\sum_{i=1}^{N}\alpha_i\cdot c\left(t-\tau_i(t)\right)\cdot d\left(t-\tau_i(t)\right)\cdot\cos\left(2\pi f_I t-\theta_i(t)\right)$$

Eq 2

Notice that the channel phase distortion only affects the carrier phase.

The delay τ_i is assumed to have linear variations with respect to time. Its value depends on two types of multipath replicas: reflected replicas and diffracted ones. These two cases are illustrated in Fig 1.

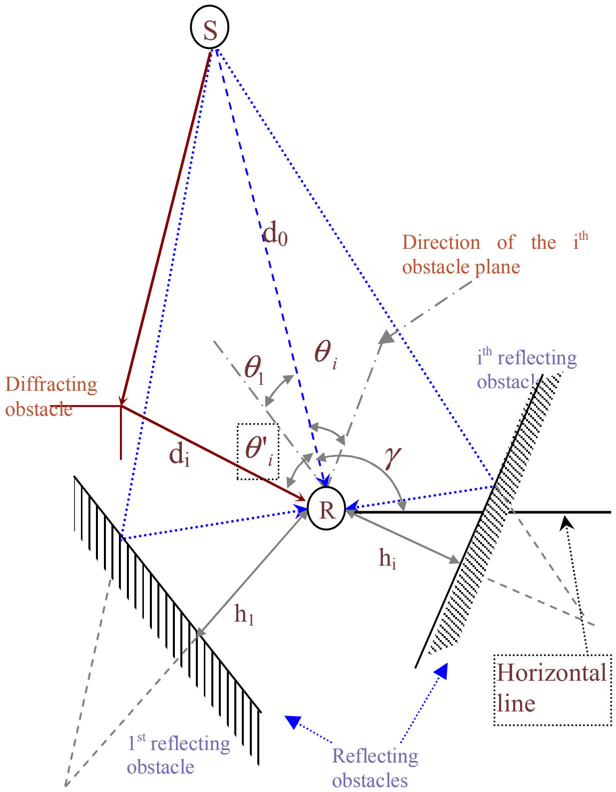

Fig 1 reflected and diffracted rays of a GPS signal. Reflected rays are in dotted lines and diffracted rays are in solid lines. The direct LOS is in dashed line.

The receiver is supposed to be at 1m above the ground level, i.e. in the hand of a user. We also suppose that it moves horizontally, and its distance with respect to obstacles varies between 0 and 5m approximately.

The delay experienced by the direct LOS ray is:

$$\tau_1 = \frac{d_0 + v_d t}{c}$$

Eq 3

Where

d_0 is the initial distance between the satellite and the receiver. It is constant throughout the simulation,

v_d is the Doppler velocity corresponding to the considered satellite elevation angle. It is given by: $v_d = \frac{v_s r_e \cos\gamma}{\sqrt{r_e^2 + r_s^2 - 2 \cdot r_e \cdot r_s \cdot \sin\gamma}}$ [Kaplan, 1996], where v_s is the satellite linear velocity, r_e is the earth's radius, r_s is the distance between the earth's centre and the satellite, γ is the satellite elevation angle. v_d is also considered constant over the duration of the simulation.

The delays experienced by the multipath replicas are defined with respect to that of the direct LOS. In the case of reflected rays, this is done using a classical model of reflection. The path followed by the reflected ray i differs from that of the direct ray (d_0) by $2h_i \sin\theta_i$, where θ_i is the angle between the direct ray and the obstacle plane. It has a random value uniformly distributed in $[0;2\pi]$. And, h_i is the distance between the receiver and the obstacle plane. h_i is also supposed to have linear variations with respect to time: $h_i = h_{0i} + v_r t \cdot \sin(\theta_i - \gamma)$, where h_{0i} is the initial distance between the receiver and the obstacle; it takes a random value between $[0m;5m]$, v_r is the receiver velocity.

Hence, the delay experienced by a reflected ray is expressed as:

$$\tau_i = \frac{d_0}{c} + \frac{v_d t}{c} + 2\frac{h_i}{c}\sin\theta_i$$

Eq 4

Where c is the light velocity.

For a refracted ray, the delay is given by the ratio of the length of the total path followed by the ray divided to the velocity of light. In Fig 1, Al-Kashi law gives:

$$\tau_i = \frac{\sqrt{(d_0 + v_d t)^2 + (d_i)^2 - 2 \cdot (d_0 + v_d t) \cdot d_i \cdot \cos(\theta_i')}}{c} + \frac{d_i}{c}$$

Eq 5

Where $d_i = \sqrt{(d_{0i})^2 + (v_r t)^2 - 2 \cdot (d_{0i}) \cdot (v_r t) \cdot \cos(\gamma - \theta_i')}$, and d_{0i} is a random initial distance that lies in $[0m;5m]$ also.

While there are much more refracted rays than reflected rays, the former are much more attenuated. This is why 80% of the multipath replicas generated will be considered as reflected rays (the less attenuated ones), and the remaining rays are considered to be refracted.

Each generated signal has a duration of 1s.

All of the results presented in this paper deal with a static user since we found that the results obtained with a dynamic user (with a velocity of 2m/s) were similar for the signal duration of 1s. This could indeed be explained by the fact that the receiver velocity is very negligible with respect to that of the satellite.

After generating the signal, we add to it white noise with a known power. The resulting value of the signal power to noise density ratio will be referred to by the input C/N_0. Then we quantify it using a 2-bits quantification process. An attenuation of approximately $1dB$ is further induced due to this quantification [Spilker et al., 1996]. Finally, we acquire the signal. Throughout the acquisition process we estimate the carrier Doppler frequency, the code delay and the C/N_0 ratio. The result is illustrated by a correlation matrix as it will be explained in the next section.

III. THE ACQUISITION ALGORITHM APPLIED

Acquisition is a coarse synchronization process giving estimates of the PRN code offset and the carrier Doppler. The code offset is due to the signal propagation. The carrier Doppler is the result of the satellites and the receiver dynamics, and of the frequency drift of the receiver local oscillator.
The estimated PRN code offset and carrier Doppler can be used to initialize the tracking loops which perform a finer search over the two parameters if the C/N_0 is sufficiently high. We assume the PRN code that must be used for despreading to be already known.

This GPS signal two-dimensional search process is defined in an uncertainty region in which code and carrier phase are aligned with the received signal. The correct alignment is identified by the measurement of the output power of the correlators (Fig 2). The result of this two dimensional search is an estimate of the code Offset to within one half chip, and of the carrier Doppler to within half the Doppler search bin size (several hundred Hz).

The acquisition scheme applied to the quantified GPS signal is based on a Fast Fourier Transform (FFT) algorithm as illustrated in the following block diagram:

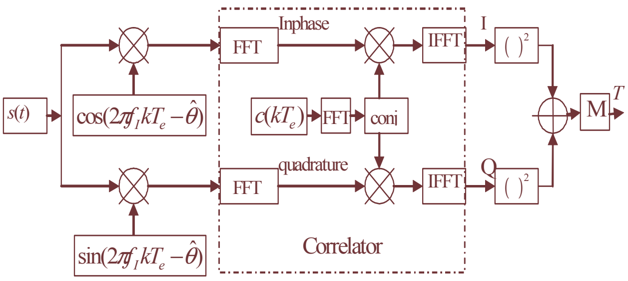

Fig 2: Acquisition process block diagram

Averaging the inphase and the quadrature components respectively, in the correlator, before squaring them is called coherent integration. The coherent integration is realized over Tp ms of signal. This reduces the impact of noise on the signal. The whole process can be repeated many times in order to further reduce the impact of noise. This is called non-coherent integration. We define M as the number of non-coherent integrations. The dwell time is then defined as the product of Tp and M. It gives the total duration of the signal being processed in the acquisition phase.

The output signal can be expressed as [Spilker et al., 1996]:

$$T = \sum_{k=1}^{M} \left(I^2(k) + Q^2(k) \right)$$

Eq 6

With

$$I(k) = \frac{A}{2} \cdot d(k) \cdot \frac{\sin(\pi \Delta f_d T_p)}{\pi \Delta f_d T_p} \cdot R_{c_f c}\left(\varepsilon_\tau(k)\right) \cdot \cos\left(\varepsilon_\theta(k)\right) + n_I(k)$$

$$Q(k) = \frac{A}{2} \cdot d(k) . \frac{\sin(\pi \Delta f_d T_p)}{\pi \Delta f_d T_p} \cdot R_{c_f c}\left(\varepsilon_\tau(k)\right) \cdot \sin\left(\varepsilon_\theta(k)\right) + n_Q(k)$$

Where Δf_d, $\varepsilon_\tau(k)$ and $\varepsilon_\theta(k)$ are the Doppler frequency, the code delay and the phase error respectively. The impact of the phase error on the useful signal is eliminated by squaring the two signal components and adding them.

n_I and n_Q are the white Gaussian correlator output noise components, with power $\sigma_{nI}^2 = \frac{N_0 f_p}{4} = \sigma_{nQ}^2$

T becomes:

$$T = \sum_{k=1}^{M} \left[\begin{array}{l} \left(\frac{A}{2} d(k) R(\varepsilon_\tau) \frac{\sin(\pi \Delta f T_P)}{\pi \Delta f T_P} \cos(\varepsilon_\theta) + n_I(k) \right)^2 \\ + \left(\frac{A}{2} d(k) R(\varepsilon_\tau) \frac{\sin(\pi \Delta f T_P)}{\pi \Delta f T_P} \sin(\varepsilon_\theta) + n_Q(k) \right)^2 \end{array} \right]$$

$$T = \sum_{k=1}^{M} \left[\frac{A^2}{4} R^2(\varepsilon_\tau) \left[\frac{\sin(\pi \Delta f T_P)}{\pi \Delta f T_P} \right]^2 + \left[n_I(k)^2 + n_Q(k)^2 \right] + N \right]$$

Eq 7

With

$$N = A \cdot d(k) \cdot R(\varepsilon_\tau) \cdot \frac{\sin(\pi \Delta f T_P)}{\pi \Delta f T_P} \cdot \cos(\varepsilon_\theta) \cdot n_I(k)$$
$$+ A \cdot d(k) \cdot R(\varepsilon_\tau) \cdot \frac{\sin(\pi \Delta f T_P)}{\pi \Delta f T_P} \cdot \sin(\varepsilon_\theta) \cdot n_Q(k)$$

The previous expression shows that the final signal contains a significant term $\frac{A^2}{4}R^2(\varepsilon_\tau)\left[\frac{\sin(\pi\Delta f T_P)}{\pi\Delta f T_P}\right]^2$ and two other noise terms that will eventually cause signal attenuation. One of these terms $n_I(k)^2 + n_Q(k)^2$ is an additive noise due to the signal propagation from the satellite to the user receiver, and the other noise term is due to the code delay and the carrier Doppler estimation errors. The next step is to find the right peak of the detection matrix. The one which is likely to correspond to the right Doppler frequency and code delay of the GPS signal studied. This is done by applying a hypothesis test *T*, called the detection criteria. In the presence of noise, a threshold is set and compared to the value of the signal at the output of the receiver (*T*). Any cell envelope that is below the threshold is detected as noise, and any cell envelope that is at or above the threshold is detected as the presence of the signal. *T* is maximum when the replica and the reference signal are aligned.

The frequency bins are a function of the coherent integration time. In our case they are equal to: $\Delta f = 1/2T_p$.

The advantage of the FFT algorithm with respect to the conventional sequential time domain technique is that it calculates, for a selected Doppler, the correlation for an entire delay range dimension of duration Tp in a single step. We assume in the following that we need to search all code delays over the whole period of the C/A code, thus using an FFT algorithm reduces the mean acquisition time.

Note that increasing the coherent integration time Tp during the acquisition process, improves the SNR ratio, because the correlator output noise power, $\sigma_n^2 = N_0 f_p / 4 = N_0 / 4T_p$ is inversely proportional to this time, and will be lowered. However, this involves more calculations and hence, is time consuming. The time consumption does not increase linearly with Tp. In fact, a higher Tp implies simultaneously an increased number of data points to be treated, and an increased number of frequency cells to be searched since the acceptable frequency uncertainty Δf is inversely proportional to Tp resulting in more frequency cells to be searched.

Another limiting factor for Tp is an eventual data bit transition, knowing that a data bit has a duration of 20ms. This problem could be avoided by setting Tp to 1ms, and increasing the number of non-coherent integrations M. But, as a result, the noise is squared. Generally, the noise compensation obtained when increasing Tp is better than that obtained when increasing M. In summary, a compromise must be found.

As a conclusion, the detection of the signal is a statistical process based on a hypothesis test:

➔Hypothesis H_0 : The signal is not present, and the considered cell contains only noise.

➔Hypothesis H_1 : The considered cell contains noise with signal present.

In the case of H_1, when the right Doppler frequency and code delay are found, the resulting attenuation is supposed to be negligible, and the value of the peak detected is supposed to be: $\max \approx \frac{A^2}{4} + m_b$, where m_b is the mean noise level. Thus the power of the useful signal is $C = \frac{A^2}{2} = 2\cdot(\max - m_b)$. In other words, once a peak is found at the end of the acquisition process, the signal power can be estimated.

During our simulations, to insure that the Doppler and the code delay found at the end of the acquisition process are accurate, these two parameters are calculated *a priori* for each signal.

The Doppler frequency can be deduced from the carrier instantaneous phase which is given by:

$$\phi_i(t) = 2\pi f_I t - 2\pi f_0 \tau_i$$

Accordingly, the instantaneous frequency is:

$$f_{inst} = \frac{1}{2\pi}\cdot\frac{d\phi_i(t)}{dt} = f_I - f_0\cdot\frac{d\tau_i}{dt} = f_I - f_{di}$$

With f_d the Doppler frequency.

This yields: $f_{di} = f_0\cdot\left(\frac{v_d}{c} + 2\frac{v_r\cdot\sin(\theta_i - elev)}{c}\cdot\sin\theta_i\right)$

For a static receiver, i.e. $v_r = 0$ m/s, the Doppler frequency of the direct LOS is given by:

$$f_{di} = f_0\cdot\frac{v_d}{c}$$

Eq 8

Next the simulation results will be presented. Note that the global acquisition time was not studied. By global acquisition time we mean the time needed to load the signal and then processing it.

IV. IMPACT OF MULTIPATH ON ACQUISITION PERFORMANCE

In order to study the impact of multipath on the acquisition performance, we will compare results obtained with a signal without multipath (i.e. just the LOS signal), with a composite signal containing a LOS and different multipath replicas, and with a composite signal without a LOS (Non-LOS). Two GPS signals are tested: that of satellite number 1 with a constant elevation angle of 30°, and that of satellite number 11 with a constant elevation angle of 45°. The multipath replicas have different relative amplitudes, phases and angle of arrivals. These parameters are not the same for the two signals. The distances between the receiver and the obstacles are not neither the same for the two signals. However, all of these parameters will be the same in the three cases described above, namely the LOS only, the LOS with multipath replicas and the Non-LOS case for a specific GPS signal.

The Doppler frequency and the code delay for the GPS signal of satellite number 1 are calculated by applying Eq 3 and Eq 8 which gives $F_d = -4666Hz$ and $\tau = 608.2758$ chips respectively. For the GPS signal of satellite number 11, the Doppler frequency and the code delay are expected to be at $-4075Hz$ and 608.2758 chips respectively.

For each of these composite signals we will try to acquire the original signal using the acquisition algorithm described in section III. We first start by setting Tp to 1ms in order to reduce the time consumption. Then we increase the value of M up to 1000 until we got the right values of Doppler frequency and the code delay. If a non-coherent integration over 1000 ms of signal, i.e. 1 second, was not sufficient we increase the value of Tp as long as the computation facilities of the processor allow doing it.

The results below show the minimum C/N_0 value that could be acquired. The first value of the C/N_0 is that of the input C/N_0. The noise introduced prior to the quantification stage represents the noise that affected the direct LOS. The second one is the C/N_0 estimated by the acquisition algorithm at the end of the acquisition. The real C/N_0 value is obtained by adding to the estimated value the attenuation due to quantification.

As it is illustrated in Fig 3 below, for a LOS signal without multipath replicas the minimum C/N_0 that could be acquired is $21dBHz$.

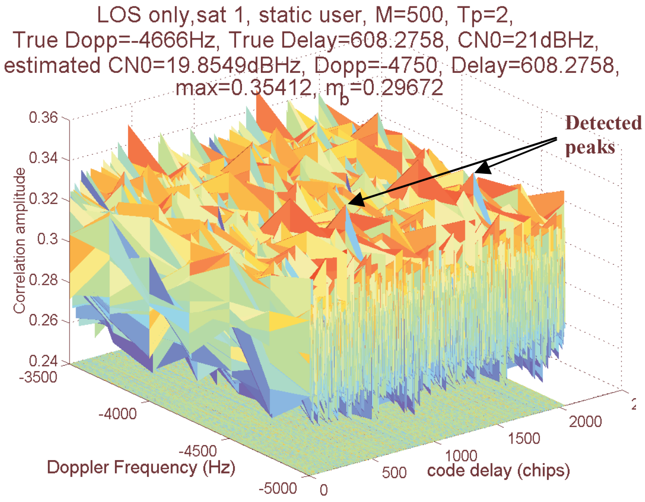

Fig 3: LOS without multipath replicas; true values: Doppler frequency -4666*Hz*, code delay 608.2758 chips, initial C/N_0 21*dBHz*; estimated values: Doppler frequency -4750*Hz*, code delay 608.2758 chips, C/N_0 19.8549*dBHz*

In the presence of a LOS with multipath replicas, the minimal C/N_0 that could be detected was also 21 $dBHz$ (Fig 4).

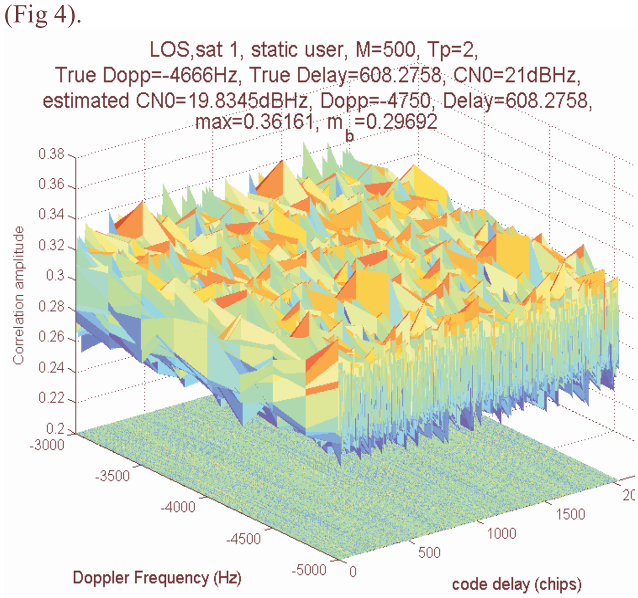

Fig 4: LOS signal with multipath replicas; true values: Doppler frequency -4666*Hz*, code delay 608.2758 chips, initial C/N_0 21*dBHz*; estimated values: Doppler frequency -4750*Hz*, code delay 608.2758 chips, C/N_0 19.8345*dBHz*

We notice that the estimated C/N_0 in these two cases is very close to the real one with an estimation error that is below $0.5dBHz$, and the values of the Doppler and the code delay are accurate. Hence multipath replicas did not disturb the acquisition process.

As depicted in Fig 5, in the case of a Non-LOS composite signal, the minimum C/N_0 ratio that could be detected is rather 40dBHz. In other words, if a direct LOS signal had a C/N_0 ratio lower than 40*dBHz* and could not reach the receiver (because of shadowing, for instance), the multipath replicas generated would not allow for finding the desired signal.

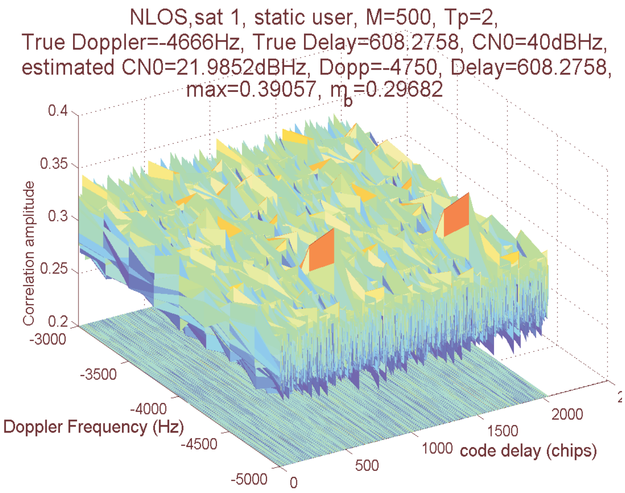

Fig 5: Non-LOS signal, multipath replicas only; true values: Doppler frequency -4666*Hz*, code delay 608.2758 chips, initial C/N_0 40*dBHz* (C/N_0 that affected the LOS that could not reach the receiver); estimated values: Doppler frequency -4750*Hz*, code delay 608.2758 chips, C/N_0 21.9852*dBHz*

In this case we found that the multipath replicas were severely attenuated with respect to the LOS.
We repeated the previous simulations with another signal, and we got similar results as depicted in Fig 6 and Fig 7

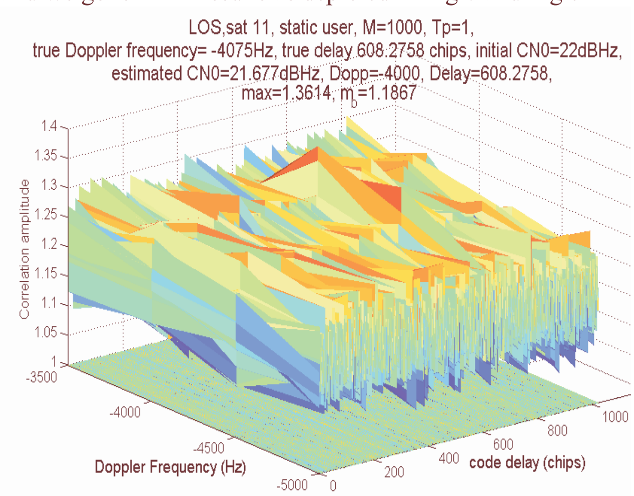

Fig 6: LOS signal with multipath replicas; true values: Doppler frequency -4075*Hz*, code delay 608.2758 chips, initial C/N_0 22*dBHz*; estimated values: Doppler frequency -4000*Hz*, code delay 608.2758 chips, C/N_0 21.677*dBHz*

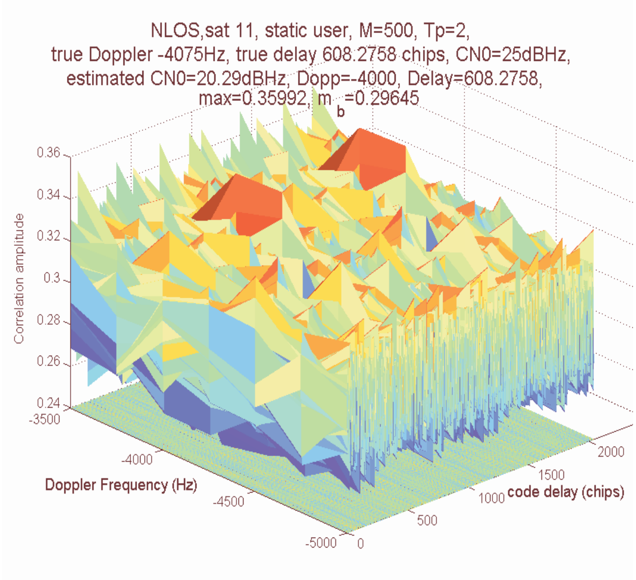

Fig 7: Non-LOS signal, multipath replicas only; true values: Doppler frequency -4075*Hz*, code delay 608.2758 chips, initial C/N_0 25*dBHz* (C/N_0 that affected the LOS that could not reach the receiver); estimated values: Doppler frequency -4000, code delay 608.2758 chips, C/N_0 20.29*dBHz*

In Fig 7, the multipath replicas were not as attenuated as in the first case. But in both Fig 5 and 7 we could acquire the signal, and we did not have errors on the Doppler and the code delay estimated.

As a conclusion, the multipath replicas have minor impact on the acquisition performance, when a direct LOS is present. In addition, even if a LOS is not available, the multipath replicas could be explored, but they are much attenuated with respect to the LOS signal. In all cases multipath replicas did not induce errors on the signal acquisition. On the other hand, in Non-LOS cases, the minimum C/N0 of the direct (masked) signal for successful acquisition depended on the indoor environment (25-40 *dBHz*).

V. IMPACT OF CROSS-ORRELATION ON ACQUISITION PERFORMANCE

After having studied the effect of multipath on signal fading in indoor environments, the next step will be to study the impact of interference between different satellite signals. In fact there are situations where a strong path may interfere with another weak path. In this case, acquiring the weak signal is very difficult, and may lead to a cross-correlation peak. This cross-correlation peak is generally expected approximately -23.9*dBHz* apart from the autocorrelation peak [Proakis, 1995]. To illustrate this situation, we used the same model that was developed for the multipath simulation, and extended it to support different satellite signals. We tried two satellite signals interfering with each other, with different powers.

We started by simulating two GPS signals (for satellites number 1 and 11) and their multipath versions, setting the C/N_0 ratio to $50dBHz$ for the first one and $25dBHz$ for the other one. Note that satellite 1 has a null Doppler, while satellite 11 has a Doppler frequency of $-4000Hz$. We tried to acquire the satellite number 11. The result of acquisition is depicted in Fig 8.

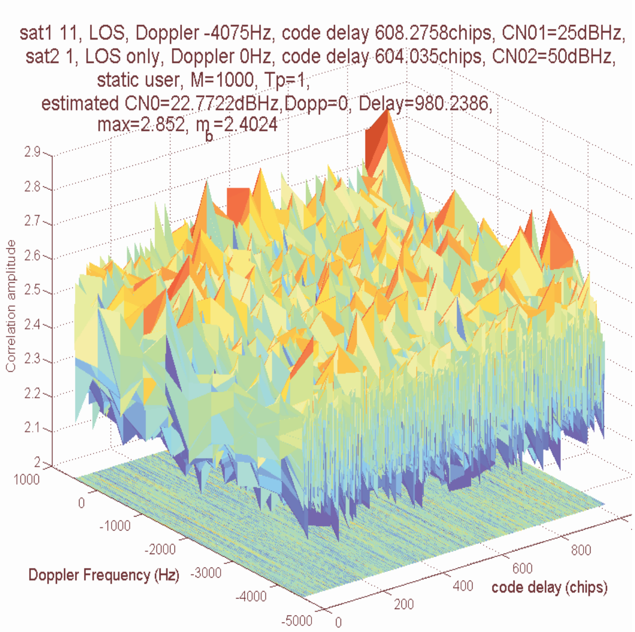

Fig 8: Cross-correlation between 2 GPS signals: 1- LOS signal of satellite number 11 with multipath replicas, true Doppler -4075*Hz*, true delay 608.2758 chips, initial C/N_0 25*dBHz* 2- LOS signal of satellite number 1 without multipath replicas, true Doppler 0*Hz*, true delay 604.035 chips, C/N_0 50*dBHz*. The signal acquired is the first one (sat1 11). Estimated values: Doppler frequency 0Hz, code delay 980.2386, C/N_0 22.7722*dBHz*

As we can see in this figure, the peak corresponds to a null Doppler which is the Doppler of satellite 1, the stronger signal. In addition, this peak is found at approximately $-27dBHz$ less than the initial C/N_0 applied to the signal of this satellite, namely 50dBHz. By adding the attenuation due to the quantification, the estimated C/N_0 corresponding to this peak will be very close to the theoretical value of approximately $-25dBHz$. This leads us to assume that the peak is very likely to be a cross-correlation one.

In order to be sure that it is a cross-correlation peak, we acquired the signal of satellite 1 alone without noise, but used the C/A code of satellite 11 in this acquisition. The detected peak has the same (Doppler frequency, code delay) couple as that of Fig 8 (in Fig 9).

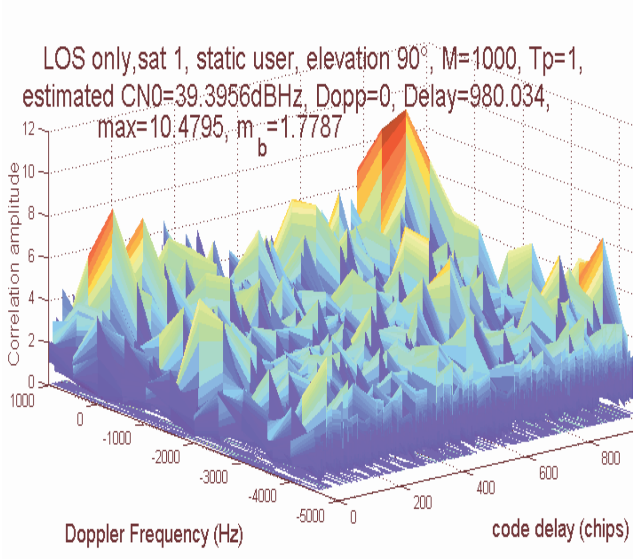

Fig 9: LOS signal of satellite number 1 without multipath replicas or noise, true Doppler 0*Hz*, true code delay 608.2758chips, signal acquired with C/A code of satellite number 11. Estimated values: Doppler frequency 0*Hz*, code delay 980.034 chips, C/N_0 39.3956*dBHz*

We notice that there is a difference of 0.2 chips approximately between the code delay estimated in the case of Fig 8, and that estimated in the case of Fig 9. In fact, the code delay uncertainty at the end of acquisition is equal to the sampling period $T_e = 1/F_e = 1/5*10^6$, since we used a sampling frequency of $5MHz$. This gives a sampling period of 0.2 μs, which corresponds to 0.2chip. Thus the difference we observed between the two figures corresponds to one code delay bin, with a duration of T_e. But in general, the code delay uncertainty needed at the end of the acquisition process is of 0.5 chip. Thus the difference observed previously is largely within this limit.

However, in general, the cross-correlation matrix is not supposed to have peaks which are stronger than others. But this is not the case in Fig 9. In other words, we were not supposed to have many strong peaks in the Doppler bin of satellite 1. This may be due to the effect of the code Doppler drift which may cancel some cross-correlation peaks.

Fig 10 illustrates another case where a cross-correlation peak is detected. We also verified that the detected peak is a cross-correlation one by the same way as before.

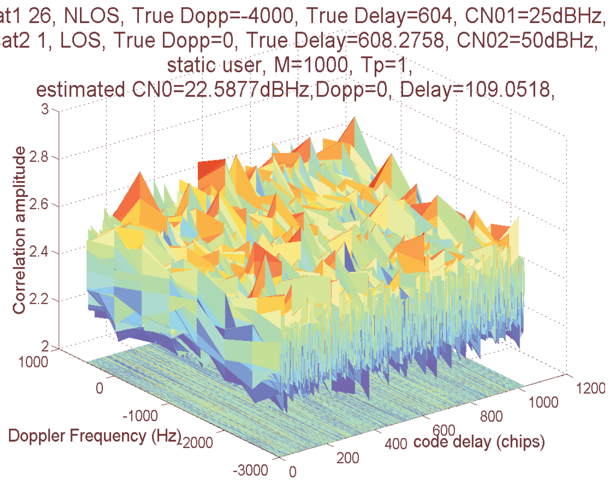

Fig 10: Cross-correlation between 2 GPS signals: 1- Non LOS signal of satellite number 26 (just multipath replicas), true Doppler -4000 *Hz*, true delay 604.0 chips, initial C/N_0 25*dBHz* 2- LOS signal of satellite number 1 with multipath replicas, true Doppler 0*Hz*, true delay 608.2758 chips, initial C/N_0 50*dBHz*. Estimated values: Doppler frequency 0*Hz*, code delay 109.0518 chips, C/N_0 22.5877*dBHz*

Fig 8 and 10 show that the cross-correlation disturbs the acquisition of a specific signal. The weakest signals presented if the previous figures, namely the signals of satellites 1 and 11 with 25 *dBHz* each, could be acquired without difficulties if the interfering signals were not present.

In conclusion, the main impact of GPS cross-correlation on the acquisition performance is a probable cross-correlation peak, which leads to inaccurate values of the Doppler frequency and the code delay, and hence to inaccuracies in the user position estimation.

Furthermore, the peak detected by the acquisition algorithm is likely to be a false alarm one. Thus it is generally difficult to verify that a peak is a cross-correlation one or not, especially when dealing with real GPS data.

VI. CONCLUSION

In this paper we investigated the impact of Multipath replicas and cross-correlation on the GPS signals acquisition.

First, we implemented an indoor time varying channel model based on a static indoor model developed by the ESA and presented in 2003. This model was used to generate three types of indoor GPS signals: a direct LOS signal, a composite LOS signal with multipath replicas, and a Non-LOS signal which contains only multipath replicas. The cross-correlation effect was studied by adding two of these signals together.

Next, we investigated the impact of multipath by testing the acquisition of these generated signals for a total dwell time of 1s, with *Tp*=1 or 2*ms*, and M=1000 or 500. The acquisition is based on a classic FFT algorithm. We focused our work on the capacity of detection of a correlation peak over the detection threshold, and we did not analyze the total time needed for acquisition.
The multipath replicas delays in this model are very negligible with respect to those of the direct LOS, thus if we detect a multipath replica it has approximately the same delay and Doppler as that of the LOS.
The results show that in the LOS cases, multipath replicas have minor effects and do not disturb the signal acquisition since they much attenuated with respect to the direct LOS. In the Non-LOS cases, even though the multipath replicas are much attenuated, they could be used to find the initial signal.

Studying the cross-correlation, we found that according to this model, a cross-correlation disturbs the acquisition performance. But no subtle conclusions could be drowned yet concerning the impact of cross-correlation.

Our future works include a deeper analysis of the signature of cross-correlation effects. This signature will be used to try and develop different mitigation techniques for indoor acquisition.

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REFERENCES

[F. Pérez-Fontán et al., 2003] - F. Pérez-Fontán , B. Sanmartin, A. Steingass, A. Lehner, J. Selva, E. Kubista, B. Arbesser-Ratsburg (2003) , *"Measurements and Modeling of the Satellite-to-Indoor Channel for Galileo"*, Proceedings of the ION-GPS-2003

[Kaplan, 1996] – Eliott D. Kaplan (1996), "*Understanding GPS: Principles and Applications*", Artech House, Norwood, MA

[Proakis, 1995] - J. G. Proakis (1995), "*Digital Communications*", Third Edition, McGraw-Hill.

[Spilker et al., 1996] - J.J Spilker Jr. and B. W. Parkinson (1996), "*Global Positioning System: Theory and Applications Volume I, American Institute of Aeronautics and Astronautics*", Inc, Washington DC.