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Probability of Detection for GNSS Signals With Sign Transitions

Myriam Foucras, Olivier Julien, Christophe Macabiau, Bertrand Ekambi, Fayaz Bacard

***Abstract*— In Global Navigation Satellite Systems (GNSS) receivers, the acquisition process is the first stage of the signal processing module. It consists of assessing the presence of GNSS signals and providing a rough estimation of the incoming signal parameters: the Doppler frequency and the code delay. However, the presence of bit sign transitions affects receiver performance in signal acquisition detection. This article focuses on the bit transition and its impact on the acquisition performance by providing a general mathematical study and an illustration for two GNSS signals: the global positioning system (GPS) legacy civil signal (L1 C/A) and Galileo E1 open service (OS). This study is led for a terrestrial user in a constraint environment. Furthermore, the presented results are mathematical models of the probability of detection in presence of bit sign transitions (only one potential bit sign transition per integration interval) and potential uncertainties on the Doppler frequency and code delay, these do not results from empirical acquisition of real signals.**

***Index Terms*—Acquisition; Bit sign transition; GNSS; Probability of detection**

I. INTRODUCTION

GLOBAL Navigation Satellite System (GNSS) signals are composed of a carrier modulated by a spreading sequence (or pseudorandom noise, PRN sequence) and a binary navigation message. Initially, the GNSS signals were only based on one component (such as GPS L1 C/A [1]) which was used for both data communication and ranging. The new generation of signals (such as GPS L1C [2], GPS L5 [3], Galileo E1 OS and Galileo E5a/b [4]) has two components. One is called the data component, which contains the navigation message and the other is the pilot component or dataless component, not modulated by a navigation data stream [4].

GNSS signal acquisition consists of assessing the presence of the GNSS signals and of providing a rough estimation of the incoming signals' parameters: Doppler and code delay. The Doppler frequency is mainly driven by the motion of the satellite, the receiver oscillator clock drift and the user dynamics [5]. In this study, it is assumed that the GNSS receiver is used for terrestrial applications (for example, a car) so the Doppler frequency range is $[-5; 5]$ kHz. The PRN code delay is related to the propagation time and hardware components [6].

The classical GNSS signal acquisition method, the serial search, is based on the use of a two-dimensional acquisition grid which should cover the uncertainty on the GNSS signal Doppler and code delay values. To detect the presence of the GNSS signal, the received signal is correlated with a succession of locally generated replicas of the GNSS signal whose parameters (Doppler and code delay) are taken from the acquisition grid. Each point of the grid then sequentially translates into an acquisition detector value and the process continues until the acquisition detector crosses a predefined threshold. For this acquisition method, the absolute value of the incoming Doppler frequency or code delay is not important, the acquisition performance depends on the relative difference between the real value and the point of the grid (called the uncertainty).

It is well known that the presence of a bit transition during the correlation process is detrimental to the signal-to-noise ratio at the correlator output and thus to the detection capability of the GNSS receiver [7]. However, few papers found in the literature investigate the mathematical model of this problem and its impact on the acquisition performance (for instance, [8] for GPS L1 C/A). The present paper intends to propose an extended study of the effect of the bit transition on the acquisition performance, including the new GNSS signals. The motivations behind this investigation are multiple:

- Understand in a general way the effect of bit transitions on the acquisition process (bit transition location, probability of bit transition, bit rate, etc…).
- Study the impact of the bit transition for different GNSS signal structures. To do so, two signals: the legacy GPS L1 C/A and the new Galileo E1 OS are taken as examples.
- Provide the probability to detect the useful signal when considering bit transitions and uncertainties on the Doppler frequency and code delay.
- Provide a theoretical dwell time to detect real signals (with bit sign transitions and random Doppler frequency and code delay) in the context of a terrestrial application and with a given average probability. Like the other

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results, the integration time is chosen so that there is a maximum of one bit sign transition per integration interval.

We have already presented results in [9] for Galileo E1 OS but theoretical and generic results presented here can be applied to any GNSS. The outline of the paper is as follows. The second section reviews the GNSS signal acquisition principle. In this section, the correlator output expressions are developed and the performance study based on a statistical test is presented. The next section is dedicated to the mathematical model of the probability of detection in presence of bit transitions. In the fourth section, always considering the bit transitions, we provide the probability to detect the signal when the estimated parameters are in the "right" cell. This permits to remove the small uncertainty because of the cell width induced by the acquisition grid. The next section applies the previous results to two GNSS signals: GPS L1 C/A and Galileo E1 OS. Results come from an implementation of the previously given model of the probability of detection in presence of bit sign transitions and uncertainties. The last section concludes the paper, giving the remaining main points of interests and results.

II. ACQUISITION

Before delving into the details of the acquisition process principle, we present the structure of the received signal. The structure and properties of signals can be completed using Interface Control Document (ICD), for GPS L1 C/A [1] and for Galileo E1 OS [4].

A. GNSS signals' Model

The signal entering the signal processing part of a GNSS receiver is a combination of GNSS signals, which are emitted by several satellites from potentially multiple constellations, and perturbations (noise, interference, etc.). The signal associated to one satellite is generically composed of the following:

- A carrier, whose frequency depends on the receiver intermediate frequency, denoted f_{IF} and Doppler frequency, denoted f_d
- A navigation message, denoted d, that can be seen as a random sequence of 1 and -1 and which bit duration is denoted T_d
- A spreading code, denoted c that is specific to each signal. A bit of a spreading code is called "chip" to mark the difference between a useful data bit and a spreading code bit. The spreading code period is denoted T_c

  A known secondary code

Based on this generic model, the received GPS L1 C/A signal at the RF front-end output can be expressed for one satellite as follows as:

$$r(t) = Ad(t-\tau)c(t-\tau)\cos(2\pi(f_d + f_{IF})t + \phi_0) + n(t) \quad (1)$$

Where:

- A is the amplitude of the incoming signal at the correlator input. In this case, A is related to the signal power C by $A = \sqrt{2C}$ (to be generic, A can be written $A = \sqrt{\beta C}$ with $\beta = 2$ for GPS L1 C/A)
- ϕ_0 is the initial phase of the incoming signal
- n is the incoming noise, which is assumed to be a white noise with centered Gaussian distribution with a constant two-sided power spectral density equal to $N_0/2$ dBW/Hz
- τ is the code delay caused by the transmission and hardware biases

The Galileo E1 OS signal has two (data and pilot) components that are in-phase. Its expression is:

$$r(t) = A\begin{bmatrix} d(t-\tau)c_D(t-\tau)p_D(t-\tau) \\ -c_2(t-\tau)c_P(t-\tau)p_P(t-\tau) \end{bmatrix} \times \cos(2\pi(f_d + f_{IF})t + \phi_0) + n(t) \quad (2)$$

Where:

- A is the amplitude of one of the component of the incoming signal at the correlator input. In this case, A is related to the total signal power C (data+pilot components) by $A = \sqrt{C}$ (and $\beta = 1$).
- c_2 is the secondary code on the pilot component. The duration of one secondary code bit is the data bit duration T_d.
- The spreading codes c_x on the data component and on the pilot component are distinguished using a subscript (x being "D" for Data and "P" for Pilot)
- p_x represents the subcarrier modulating the spreading codes for composite binary offset carrier (CBOC) signals [4]. It is different between the data and pilot components.

For Galileo E1 OS, the power of the signal is equally distributed on both components (50% on each). In this paper, it is assumed that the total received power is the same for GPS L1 C/A and for Galileo E1 OS signals (considering both components).

Up to the section IV, only one component is considered. The structure and properties of the data component are the same as those of the pilot component and the secondary code has an effect similar to that of a data sequence during the acquisition stage.

B. GPS L1 C/A and Galileo E1 OS Signals Characteristics

The characteristics of the civil GPS and Galileo signals in the L1 band are given in TABLE I.

TABLE I
GPS L1 C/A AND GALILEO E1 OS SIGNAL TECHNICAL CHARACTERISTICS

Signal	GPS L1 C/A	Galileo E1 OS	
		Data	Pilot
Spreading modulation	BPSK	CBOC(6, 1, 1/11, '+')	CBOC(6, 1, 1/11, '-')
Code frequency	1.023 MHz	1.023 MHz	
Spreading code length	1023 chips $T_c = 1$ ms	4092 chips $T_c = 4$ ms	
Bit rate	50 bit/s	Data 250 bit/s	Secondary code 250 bit/s
Bit duration	$T_d = 20$ ms	$T_d = 4$ ms	$T_{c_2} = 4$ ms

It is worth noting that:

- For GPS L1 C/A, the data bit duration is 20 times longer than spreading code period. This implies that a data bit

sign transition occurs only once every twenty spreading code periods with a probability of 50 %.
- For Galileo E1 OS, the spreading code period is the same as the duration of a data or secondary code bit. This implies that a bit sign transition (data bit and/or secondary code bit) occurs at each spreading code period with a probability of 50 %.

C. Acquisition Principle

For now, the acquisition principle is presented when one component is considered. The acquisition process is based on a correlation operation. A local replica of the received signal (composed exclusively of the carrier, the spreading code and optionally the secondary code) is correlated with the received signal. By generating a set of local replicas that take all possible values for the carrier frequency and spreading code delay of the incoming signal (called as uncertainty space) and using a relevant detector, it is possible to roughly estimate two parameters of the incoming signal: the Doppler frequency and the code delay. One classical acquisition strategy [10] is the serial-search acquisition method, which consists of testing successively many possible (carrier frequency and spreading code delay) couples based on a discretization of the uncertainty space [11]. Let Δ_f be the uncertainty width in the frequency search space and Δ_τ be the uncertainty width in the code delay search space.

D. Correlator Outputs in Absence of Data

Let us study the acquisition process in an ideal case, which assumes that there is no data in (1). This is equivalent to assume that d is constant and equal to 1.
The general structure of the sequential acquisition is depicted in Fig. 1 and [12].

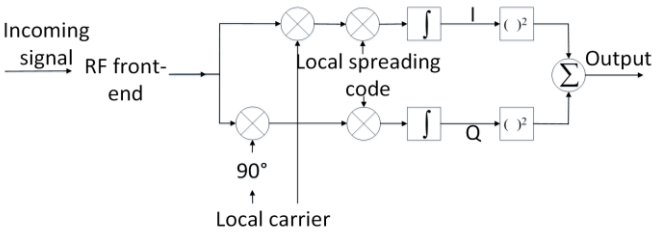


Fig. 1: Block diagram of the serial search acquisition

The local code delay and carrier replicas are modeled as:
- $c(t-\hat{\tau})$ where $\hat{\tau}$ is the local code delay
- $\cos\left(2\pi\left(f_{IF}+\widehat{f_d}\right)t\right)$, where $\widehat{f_d}$ is the local Doppler frequency

Assume that $[T_0 + kT_I;\ T_0 + (k+1)T_I]$ is the coherent integration interval (with T_I as an integer multiple of the spreading code period and shorter or equal to a bit duration $T_I \leq T_d$) and that parameters of the processed signal and the local replica are constant during the correlation operation such that the code delay error ε_τ and the Doppler frequency error ε_f are constant and the carrier phase error at the beginning of the correlation process is ε_{ϕ_0}. Then, it is possible to show [6] that the in-phase correlator output, denoted $I(k)$ in Fig. 1 can be modeled by:

$$I(k) = \frac{A}{2}R(\varepsilon_\tau)\cos\left(\pi\varepsilon_f T_I + \varepsilon_{\phi_0}(k)\right)\mathrm{sinc}\left(\pi\varepsilon_f T_I\right) + n_I(k) \quad (3)$$

where
- n_I represents the noise at the in-phase correlator output, which is assumed to follow a centered Gaussian distribution whose variance is $\sigma^2 = \frac{N_0}{4T_I}$ [13]
- R is the correlation function between the local and the incoming spreading sequence (including the sub-carrier)

The quadrature-phase correlator output, represented as Q in Fig. 1 is:

$$Q(k) = \frac{A}{2}R(\varepsilon_\tau)\sin\left(\pi\varepsilon_f T_I + \varepsilon_{\phi_0}(k)\right)\mathrm{sinc}\left(\pi\varepsilon_f T_I\right) + n_Q(k) \quad (4)$$

where n_Q is the noise at the quadrature correlator output which has the same distribution as n_I but is independent from it.

E. Acquisition as a Detection Problem

The acquisition process can be seen as a detection problem because the purpose of the acquisition is to detect whether a signal from a given satellite is present at the receiver level [8]. The usual acquisition detector is expressed as:

$$T = \sum_{k=1}^{K}\left(\frac{I^2(k)}{\sigma^2} + \frac{Q^2(k)}{\sigma^2}\right) \quad (5)$$

where K is the number of non-coherent summations. The duration KT_I is the dwell time in an acquisition bin.
The detector is then compared to a predefined threshold T_h to declare whether the signal is present. In this context, false alarms and missed detection are possible. The probability of false alarm P_{fa} is generally small and in this paper, fixed to $P_{fa} = 10^{-3}$, as in [14].

The detection problem can be seen as a hypothesis test with the following hypothesis:
- The null hypothesis H_0 assumes that the useful signal is not present in the incoming signal or that the investigated cell of the acquisition grid is not the correct one. Because of the correlation properties of the GNSS spreading codes, these two cases can be grouped. In other words, it can be assumed that there is only noise at the correlator outputs.
- The alternative hypothesis H_1 assumes that the useful signal is present and that the investigated cell of the acquisition grid is the correct one.

The acquisition detection test can be re-written as:

$$H_0: T < T_h \text{ against } H_1: T \geq T_h \quad (6)$$

1) Hypothesis H_0

Let us consider the null hypothesis and determine the detection threshold knowing the desired probability of false alarm. Under this hypothesis, the correlator outputs (3) and (4) can be seen as only noise. Then I and Q have centered Gaussian distribution whose variance is equal to σ^2. The division of I^2 and Q^2 by σ^2 permits us to normalize the correlator outputs to have unit Gaussian random variables. Then, the detector under the null hypothesis, T_{H_0}, follows a χ^2 distribution with $2K$ degrees of freedom whose cumulative distribution function is denoted F_{χ^2}.

$$T = \sum_{k=1}^{K} \left(\frac{I^2(k)}{\sigma^2} + \frac{Q^2(k)}{\sigma^2} \right) \sim_{H_0} \chi^2(2K) \quad (7)$$

For a desired probability of false alarm, P_{fa}, the detection threshold can be easily deduced:

$$P_{fa} = P_{H_0}(\mathrm{T} > T_h) = 1 - F_{\chi^2(2K)}(T_h) \quad (8)$$

2) Hypothesis H_1

Let us assume that the useful signal is present and study the of detecting the presence of the GNSS signal. It can be assumed that ε_f and ε_τ are small (within the acquisition cell uncertainty space). The distributions of the correlator outputs are given by:

$$\begin{aligned} I(k) &\sim \mathcal{N}(E[I(k)], \sigma^2) \\ Q(k) &\sim \mathcal{N}(E[Q(k)], \sigma^2) \end{aligned} \quad (9)$$

Where $E[.]$ is the expectation operator. The detector is then characterized by the following:

$$T = \sum_{k=1}^{K} \left(\frac{I^2(k)}{\sigma^2} + \frac{Q^2(k)}{\sigma^2} \right) \sim_{H_1} \chi^2(2K, K\lambda_0) \quad (10)$$

The distribution of the acquisition detector becomes a noncentral χ^2 distribution. Assuming that the parameters of $I(k)$ and $Q(k)$ remain the same during the dwell time in one acquisition grid cell, the non-centrality parameter is equal to $K \times \lambda_0$where

$$\lambda_0 = \beta \frac{C}{N_0} \times T_I R^2(\varepsilon_\tau) \mathrm{sinc}^2(\pi \varepsilon_f T_I) \quad (11)$$

Knowing the distribution of the detector, it is possible to evaluate the probability of detection, P_{d_0}:

$$P_{d_0} = P_{H_1}(\mathrm{T} > T_h) = 1 - F_{\chi^2(2K, K\times\lambda_0)}(T_h) \quad (12)$$

For relatively small Doppler frequency error as in this study, it can be seen from this expression that the probability of detection depends on the following:

- The received carrier-to-noise ratio *C/N₀* (the higher, the better)
- The integration time T_I (the longer, the better)
- The Doppler frequency and code delay errors ε_f and ε_τ (the smaller, the better)
- The number of noncoherent summations *K* (the higher, the better)

As an example, a representation of the acquisition detector for each couple of the acquisition grid is given in Fig.2 for GPS L1C/A.

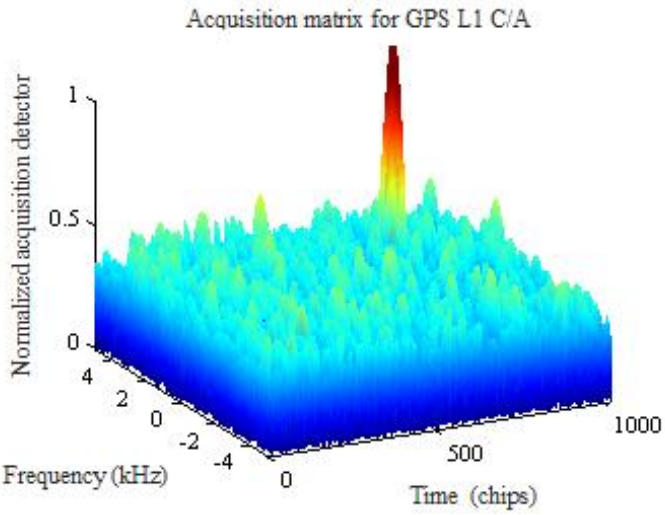


Fig. 2: Acquisition matrix output from serial search acquisition

F. Acquisition parameters

The choice of the acquisition cell size comes from a compromise between minimizing ε_f and ε_τ to have a better probability of detection and minimizing the number of cells to reduce the acquisition time. In the context of this paper, it was decided to follow the recommendations given in [14]:

- $|\Delta_f| \leq \frac{1}{2T_I}$
- $|\Delta_\tau| \leq \frac{1}{2}$ chip for GPS L1 C/A and in an equivalent way $|\Delta_\tau| \leq \frac{1}{6}$ chip for Galileo E1 OS.

Such a cell size results in a worst-case degradation in terms of equivalent *C/N₀* at the correlator output of approximately 3.5 dB, which comes from the possibility that the actual incoming parameters are at the edge of the correct acquisition cell.

III. BIT SIGN TRANSITION

In this paper, it is assumed that the acquisition is done in cold start, meaning that there is no a-priori information used by the receiver. In this context, the location of the data bit transition in the correlation interval is unknown. Considering this case, the correlation operation, and thus the detection performance results, can become radically different. The following section develops the associated mathematical model and describes the impact of bit sign transitions on the acquisition of GNSS signals.

Before looking at the problem of the bit sign transition on the acquisition performance, let us define the terminology used in the following:

- A bit transition is defined as the transition between 2 consecutive bits of the useful data sequence or secondary code
- During a bit transition, a sign transition can occur. Assuming that the data sequence is random and each bit value is independent from the previous one, a sign transition occurs with a probability of 50%.

A. *Correlator outputs in presence of bit sign transition*

The correlator output model can be established by considering that a bit sign occurs. Let us assume that the following:

- The correlation time is assumed to be shorter than the data bit duration $T_I \leq T_d$; then, at the maximum, one bit sign transition can occur within the correlation interval
- The correlation interval is chosen to be $[0; T_I]$
- A bit sign transition occurs at t_0 with $0 \leq t_0 \leq T_I$. For example,

$$d(t) = \begin{cases} +1, t \in [0; t_0] \\ -1, t \in [t_0; T_I] \end{cases} \quad (13)$$

Fig. 3 illustrates the previously presented assumptions. Here, two bit transitions are represented but there is only one bit sign transition between the bit *n* and the bit *n+1*.

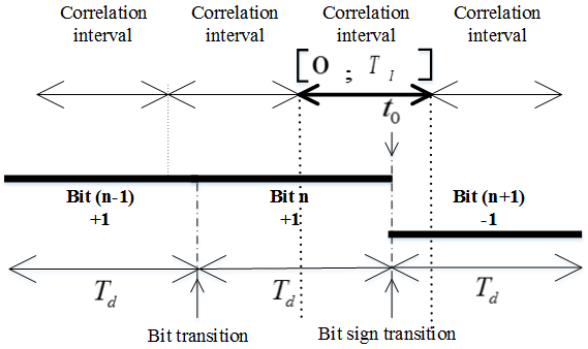


Fig. 3: Bit sign transition scheme

With these assumptions, let us evaluate the in-phase correlator output:

$$I_{t_0}(k) = \frac{1}{T_I}\int_0^{t_0} r'^{(t-\tau)} c(t-\hat{\tau}) \cos\left(2\pi\left(f_{IF} + \hat{f}_d\right)t\right)dt - \frac{1}{T_I}\int_{t_0}^{T_I} r'(t-\tau) c(t-\hat{\tau}) \cos\left(2\pi\left(f_{IF} + \hat{f}_d\right)t\right)dt \quad (14)$$

where $r'(t-\tau)$ is the received signal $r(t-\tau)$ without the data bit. Using trigonometric identities $I_{t_0}(k)$ becomes:

$$I_{t_0}(k) = \frac{A}{2} R(\varepsilon_\tau) \left[-\sin\left(\pi\varepsilon_f T_I + \varepsilon_{\phi_0}(k)\right) \frac{\cos(\pi\varepsilon_f T_I)}{2\pi\varepsilon_f T_I} + \frac{\sin(2\pi\varepsilon_f t_0 + \phi_0)}{2\pi\varepsilon_f T_I} \right] + n_{I_{t_0}}(k) \quad (15)$$

Similarly, the quadrature correlator output, $Q_{t_0}(k)$, in the presence of a bit sign transition at t_0 is as follows:

$$Q_{t_0}(k) = \frac{A}{2} R(\varepsilon_\tau) \left[-\cos\left(\pi\varepsilon_f T_I + \varepsilon_{\phi_0}(k)\right) \frac{\cos(\pi\varepsilon_f T_I)}{2\pi\varepsilon_f T_I} + \frac{\cos(2\pi\varepsilon_f t_0 + \phi_0)}{2\pi\varepsilon_f T_I} \right] + n_{Q_{t_0}}(k) \quad (16)$$

B. *Impact on acquisition when no non-coherent summation is used*

Considering that the acquisition is only based on one set of correlator output ($K = 1$), then in the presence of a data bit transition (in this section, we assume that the bit sign transition occurs within the correlation interval), the normalized acquisition detector, becomes:

$$T_{t_0} = \frac{I_{t_0}^2(k)}{\sigma^2} + \frac{Q_{t_0}^2(k)}{\sigma^2} \quad (17)$$

Similar to the hypothesis test in Section II.E, under H_0, T_{t_0} has the same distribution as the T: χ^2 distribution with 2 degrees of freedom. Under H_1, T_{t_0} becomes a noncentral χ^2 distribution with 2 degrees of freedom, and the noncentrality parameter is λ_{t_0} (a function of the instant of the bit sign transition t_0):

$$\lambda_{t_0} = \beta \frac{C}{N_0} T_I R^2(\varepsilon_\tau) \times \frac{\cos^2(\pi\varepsilon_f T_I) + 1 - 2\cos(\pi\varepsilon_f T_I)\cos\left(\pi\varepsilon_f (T_I - 2t_0)\right)}{\left(\pi\varepsilon_f T_I\right)^2} \quad (18)$$

Fig. 4 represents the noncentrality parameter λ_{t_0} as a function of the Doppler frequency error and the bit transition instant in a coherent integration time of 1 ms (GPS L1 C/A) for a received signal power of 27 dB-Hz.

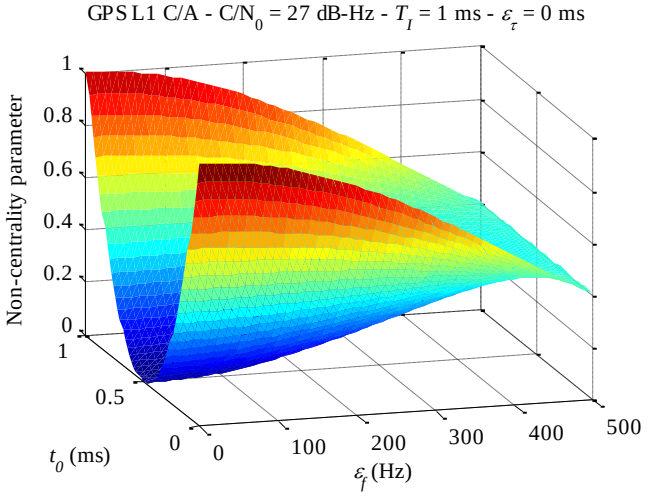


Fig. 4: Non-centrality parameter in presence of a bit sign transition

Fig. 4 and (18) help to show that degradation of the noncentrality parameter λ_{t_0} with respect to λ_0 depends on the Doppler frequency error ε_f and the location of the bit sign transition t_0. The worst location for the bit sign transition is in the middle of the correlation interval ($t_0 = T_I/2$). In this case, for $\varepsilon_f \neq 0$,

$$\lambda_{t_0} = \beta \frac{C}{N_0} T_I R^2(\varepsilon_\tau) \frac{\left(1 - \cos(\pi\varepsilon_f T_I)\right)^2}{\left(\pi\varepsilon_f T_I\right)^2} \quad (19)$$

Let us assess the effect of the bit sign transition on the non-centrality parameter λ_{t_0}.In the case of the GPS L1 C/A signal, if t_0 is a multiple of T_I, meaning that the bit sign transition occurs at the beginning of the spreading code period, then it is as if no bit sign transition occurred. If $\varepsilon_f = 0$, then λ_{t_0} needs to be assessed carefully because ε_f is in the denominator in (18). Replacing $u = \pi\varepsilon_f T_I$ in (18) and knowing that when u is in the neighborhood of 0, $\cos(u)$ can be approximated by $\left(1 - \frac{u^2}{2}\right)$, it follows that

$$\cos^2(u)+1=\frac{1+\cos(2u)}{2}+1 \approx_{u\approx 0} 2-u^2=2\left(1-\frac{u^2}{2}\right) \quad (20)$$

$$2\cos(u)\cos\left(u\left(1-\frac{2t_0}{T_I}\right)\right) \approx_{u\approx 0} 2\left(1-\frac{u^2}{2}\right)\left(1-\frac{u^2}{2}\left(1-\frac{2t_0}{T_I}\right)^2\right) \approx_{u\approx 0} 2\left(\left(1-\frac{u^2}{2}\right)-\left(1-\frac{u^2}{2}\right)\frac{u^2}{2}\left(1-\frac{2t_0}{T_I}\right)^2\right) \quad (21)$$

Then, it follows that around 0:

$$\frac{2\left(1-\frac{u^2}{2}\right)-2\left(1-\frac{u^2}{2}\right)+2\left(1-\frac{u^2}{2}\right)\frac{u^2}{2}\left(1-\frac{2t_0}{T_I}\right)^2}{u^2} \approx_{u\approx 0}\left(1-\frac{u^2}{2}\right)\left(1+4\frac{t_0^2}{T_I^2}-4\frac{t_0}{T_I}\right) \quad (22)$$

This leads to the following approximation of λ_{t_0} for $\varepsilon_f \approx 0$,

$$\lambda_{t_0} \approx \beta\frac{C}{N_0}T_I R^2(\varepsilon_\tau)\left(1+4\frac{t_0^2}{T_I^2}-4\frac{t_0}{T_I}\right) \quad (23)$$

In this case, if t_0 is equal to $T_I/2$, λ_{t_0} is null.

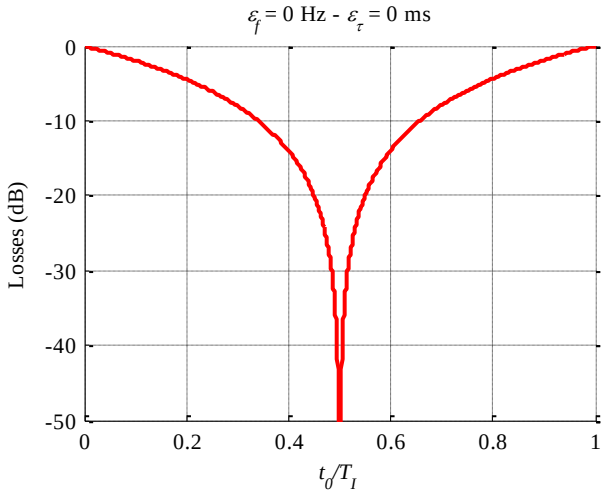


Fig. 5: Losses on the probability of detection due to bit sign transition

The losses on the non-centrality parameter considering one bit transition and no Doppler and code delay errors are represented in Fig. 5. This figure clearly shows that the effect of the sign transition can be important for a transition close to the center of the integration interval. This should induce a strong degradation of the probability of detection compared to the case without data bit sign transitions.

To conclude this section, the probability of detection for one integration ($K=1$) knowing that a bit sign transition occurs at t_0 during the correlation interval is as follows:

$$P_{d_{1,t_0}} = 1 - F_{\chi^2(2,\lambda_{t_0})}(T_h) \quad (24)$$

C. Generalization of the Probability of Detection to Any Number of Noncoherent Summations

The previous analysis can be extended over several noncoherent summations to give the general expression of the probability of detection. Knowing that over the dwell time KT_I, exactly, N bit transitions occur (which can depend on the considered slice of received signal), the average probability of detection noted as P_{d,t_0} is then:

$$P_{d,t_0} = \sum_{n=0}^{N} P_n \times P_{d_{n,t_0}} \quad (25)$$

where

- P_n represents the probability of occurrence of n bit sign transitions over the dwell time (which depends on K and T_I)
- $P_{d_{n,t_0}}$ represents the probability of detection knowing that n bit sign transitions occur over the dwell time (and thus exactly n correlator output pairs are affected by these transitions according to our assumptions) . This quantity depends on ε_τ, ε_f, T_I, K and the location of transition t_0. It can be expressed as

$$P_{d_{n,t_0}} = 1 - F_{\chi^2(2,\lambda)}(T_h) \quad (26)$$

where $\lambda = n \times \lambda_{t_0} + (K-n) \times \lambda_0$

D. Average Probability of Detection

The randomness of the location of t_0 has an impact on the computation of the average probability of detection. Let us define the maximum number of bit transitions within the dwell time as follows:

$$N_{max} = \left\lceil \frac{KT_I}{T_d} \right\rceil \quad (27)$$

If there can be several correlations per data bit, $T_I \leq T_d$, (for instance GPS L1 C/A), two cases have to be considered. For example, for GPS L1 C/A, for dwell time $KT_I = 35$ ms, $N_{max} = 2$: however, in 25 % of the cases, only one bit sign transition can occur within the dwell time (when the second bit transition is in the interval [35; 40] ms) and in 75 % of the cases, two bit sign transitions can occur. The percentage of $N_{max} - 1$ bit sign transitions is in fact given by the following:

$$\alpha = N - \frac{KT_I}{T_d} = \left\{\frac{KT_I}{T_d}\right\} \quad (28)$$

Taking this into account, the general expression of the probability of detection becomes:

$$\forall\, T_I \leq T_d \text{ such as } \frac{T_d}{T_I} \in \mathbb{N}, \forall K \in \mathbb{N}^*, P_{d,t_0} = \frac{\alpha}{2^{N-1}}\sum_{n=0}^{N_{max}-1}\binom{N_{max}-1}{n}P_{d_{n,t_0}} + \frac{1-\alpha}{2^N}\sum_{n=0}^{N_{max}}\binom{N_{max}}{n}P_{d_{n,t_0}} \quad (29)$$

where $P_{d_{n,t_0}}$, defined in (26), takes into account the number of correlations affected by a bit sign transition through the noncentrality parameter.

In (28) and (29), $P_{d_{n,t_0}}$ depends upon a number of factors, including the location of the bit sign transition t_0 and the Doppler and code delay errors (ε_f and ε_τ respectively) because of the acquisition bin size and they all affect the value of λ. It

is thus better look at an average performance when taking into account these parameters.

To do so, it can be assumed that the Doppler frequency and the code delay uncertainties of the incoming signal in the correct acquisition bin are uniformly distributed. Taking the example of GPS L1 C/A and assuming correlation duration of $T_I = 1$ ms, the size of one acquisition cell is $[-250; 250]$ Hz $\times$ $[-0.25; 0.25]$ chip. Following this example, for a C/N_0 of 40 dB-Hz, and the context of a potential bit sign transition and no noncoherent summations Fig. 6 represents, the bit sign transition and no non-coherent summations:

- The actual probabilities of detection within the right cell (color coded from blue to red)
- The average probability of detection over the whole acquisition cell (in green).

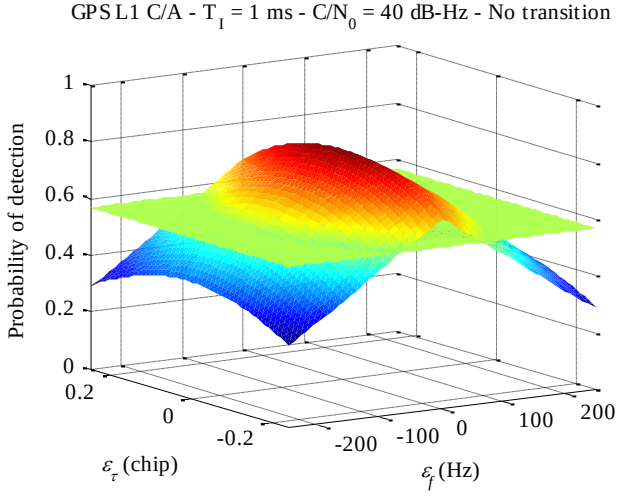


Fig. 6: Probabilities of detection for each bin in the right cell

Similarly, to assess the average effect of the bit sign transition on the probability of detection, it is proposed to take into account the location of the bit transition as a random variation. In the following, this random variable is assumed to be uniformly distributed over the data bit (or secondary code) duration. To conclude, the average probability of detection knowing that n bit sign transitions occur over the dwell time is given by the following:

$$\overline{P_d} = \mathrm{E}_{correct\ cell, t_0}\left[P_{d,t_0}\right] \tag{30}$$

IV. APPLICATION TO GNSS SIGNALS

To illustrate the previous generic results, two GNSS signals are studied as example. As presented in Section II.A, these signals exhibit quite different structures. In particular, Galileo E1 OS is representative of the new generation of GNSS signals.

A. GPS L1 C/A

1) Optimal Acquisition Parameters

To remain focused on a specific case (which represents reality), the correlation duration considered here does not exceed the data bit duration for GPS L1 C/A (20 ms). There are thus several choices for T_I.

Fig. 7. represents the case in which 1 ms correlations are used. Of more 20 successive 1-ms correlations, only 1 correlation can be affected by a data bit transition, which involves a bit sign transition with a probability of 50 %. The 19 other 1-ms correlations will necessarily be free of bit transitions.

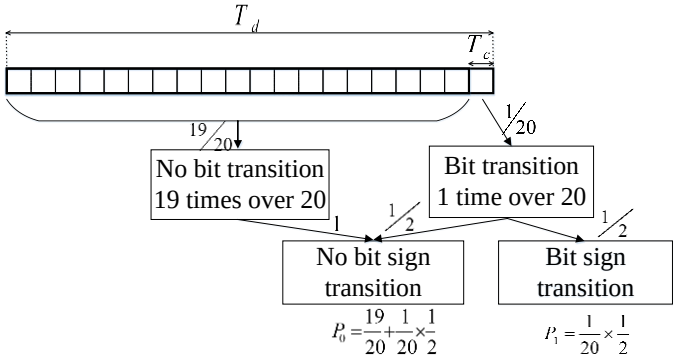


Fig. 7: Scheme to determine the probability of detection (GPS L1 C/A)

Based on (25), and for all possible T_I such that T_I is a multiple of the PRN code duration and $T_I \leq T_d$. TABLE II gives the average probability of detection P_{d,t_0} for the simple case of $K = 1$. It is a linear combination of the probability of 0 or 1 bit sign transition with:

$$\begin{aligned} P_{d_{0,t_0}} &= P_{d_0} = 1 - F_{\chi^2(2,\lambda_0)}(T_h) \\ P_{d_{1,t_0}} &= 1 - F_{\chi^2(2,t_0)}(T_h) \end{aligned} \tag{31}$$

The parameters λ_0 and λ_{t_0} depend on the coherent integration time T_I as given in (11) and (18); thus P_{d_0} and $P_{d_{1,t_0}}$ are different for each value of T_I.

TABLE II
AVERAGE PROBABILITY OF DETECTION FOR GPS L1 C/A FOR ONE INTEGRATION

T_I	$P_{d_{t_0}} = P_0 \times P_{d_0} + P_1 \times P_{d_{1,t_0}}$
1 ms	$\left(\frac{19}{20} + \frac{1}{20} \times \frac{1}{2}\right) P_{d_0} + \left(\frac{1}{20} \times \frac{1}{2}\right) P_{d_{1,t_0}}$
2 ms	$\left(\frac{9}{10} + \frac{1}{10} \times \frac{1}{2}\right) P_{d_0} + \left(\frac{1}{10} \times \frac{1}{2}\right) P_{d_{1,t_0}}$
4 ms	$\left(\frac{4}{5} + \frac{1}{5} \times \frac{1}{2}\right) P_{d_0} + \left(\frac{1}{5} \times \frac{1}{2}\right) P_{d_{1,t_0}}$
5 ms	$\left(\frac{3}{4} + \frac{1}{4} \times \frac{1}{2}\right) P_{d_0} + \left(\frac{1}{4} \times \frac{1}{2}\right) P_{d_{1,t_0}}$
10 ms	$\left(\frac{1}{2} + \frac{1}{2} \times \frac{1}{2}\right) P_{d_0} + \left(\frac{1}{2} \times \frac{1}{2}\right) P_{d_{1,t_0}}$
20 ms	$\frac{1}{2} P_{d_0} + \frac{1}{2} P_{d_{1,t_0}}$

To illustrate TABLE II, Fig. 8 provides the average probability of detection for different C/N_0 values and for a dwell time of 20 ms. The maximum average probability per C/N_0 is denoted with a star, allowing us to determine the optimal coherent integration time. As can be observed, the higher the C/N_0 is, the lower the coherent integration time.

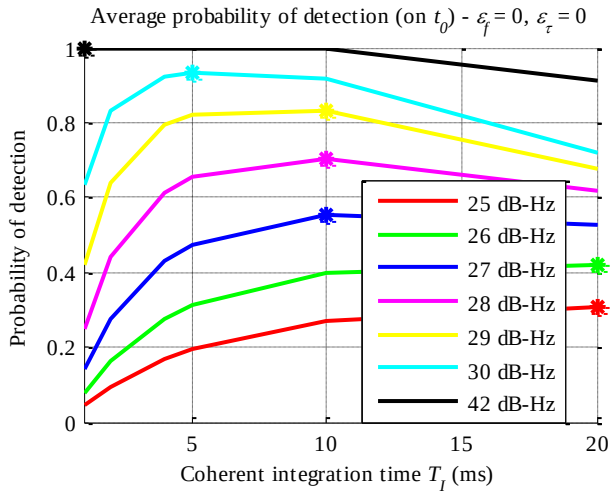


Fig. 8: Average probability of detection for different C/N_0 values, for a dwell time of 20 ms

Based on (29), which is the generic expression of the average probability of detection, it is possible to determine via simulations the best couple (K, T_I) to minimize the dwell time on one cell while ensuring a desired probability of detection. Taking as an example the objective to reach an average probability of detection of 95 % for weak C/N_0 values, TABLE III gives the minimum dwell time KT_I to reach the objective and the associated coherent integration time T_I for which the probability of detection is the lowest above 95% using the following factors:

- The bit sign transition is not considered and there are no Doppler and code delay uncertainties (center of the right bin),
- The bit sign transition occurs in the worst location ($t_0 = T_I/2$) and there are no Doppler and code delay uncertainties,
- A random location of the bit sign transition location, as described earlier, and there are no Doppler and code delay uncertainties.

The first column (dwell time KT_I) and second column (correlation duration T_I) for each case allow us to determine the corresponding number of noncoherent summations K.

TABLE III
OPTIMAL CORRELATION TIME TO REACH A PROBABILITY OF DETECTION OF 95% (GPS L1 C/A) WITH $\varepsilon_f = 0$ AND $\varepsilon_\tau = 0$

C/N_0 (dB-Hz)	No transition considered		Bit sign transition considered at worst location ($t_0 = T_I/2$)		Bit sign transition considered as random	
	Dwell time (ms)	T_I (ms)	Dwell time (ms)	T_I (ms)	Dwell time (ms)	T_I (ms)
25	60	20	120	5-10	100	10
26	40	20	85	5	80	5-10
27	**40**	**10-20**	**64**	**4**	**60**	**5-10**
28	30	10	45	5	40	10
29	20	10-20	35	5	30	10
30	20	4-5-10-20	25	5	24	4
31	15	5	20	4-5	20	4-5-10
32	10	10	15	5	15	5
33	8	4	12	2-4	10	5

It can be seen that for low C/N_0 values, the optimal dwell time when considering the data bit sign transitions is twice that for when the data bit sign transitions are not considered. It can be also seen that the optimal acquisition parameters when bit sign transitions are considered differ significantly from the case in which they are not considered (which is often found in the literature or simplified to a considered T_I of 1 ms). The optimal values for T_I depend on the targeted C/N_0. It is essential to consider the presence of data when deciding upon the acquisition parameters.

To correctly consider the previous results, it is important to put them in perspective. When dealing with acquisition performance, two criteria are critical: the mean acquisition time [15] and the sensitivity. In the context of this paper, we focus only on the sensitivity. However, the choice of the optimal coherent integration duration, as presented earlier also affects the number of Doppler and thus the time to explore the whole acquisition grid. As a consequence, the truly optimal coherent integration duration also has to be based on the mean acquisition time.

2) *Probability of Detection Considering Bit Sign Transitions and Doppler and Code Delay Residual Errors*

In the following, the specific case of a GPS L1 C/A signal received with a C/N_0 value of 27 dB-Hz is studied. The objective is to understand the degradation of the probability of detection because of the joint effect of bit sign transitions, Doppler and code delay residual errors. Fig. 9 provides the average probability of detection taking into account the residual errors and bit sign transitions as a function of the dwell time for six values of the correlation duration T_I. Fig. 9 shows that for a C/N_0 value of 27 dB-Hz, the optimal correlation duration T_I is 5 ms or 10 ms. It appears that $T_I = 5$ ms is probably more adapted for a C/N_0 greater than 27 dB-Hz and it is not as important to use long correlations. When looking at the actual probability of detection, it appears

that the effect of the acquisition cell size is important: in the case of a 60 ms dwell time, the best probability of detection is 85 % while Table III (not considering code delay and Doppler errors) showed 95 %.

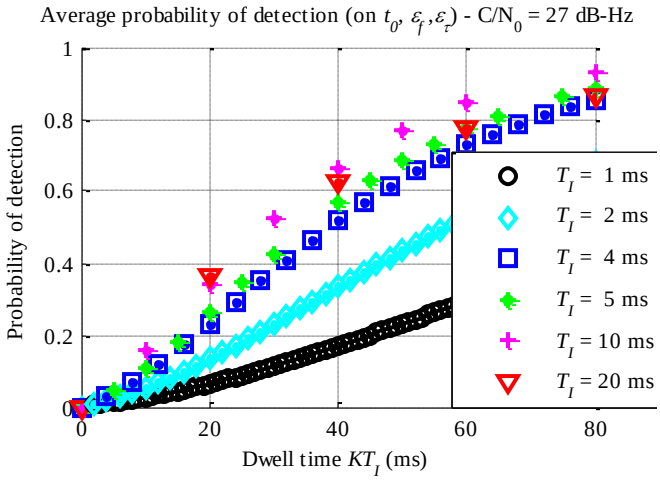


Fig. 9: Average probability of detection at 27 dB-Hz for GPS L1 C/A (with bit sign transitions and residual code delay and Doppler errors)

For a high C/N_0, the effect of the data bit sign transition is not as pronounced because the optimal dwell time can be short (1 ms) and thus less affected by bit transitions.

In this paper, the theory has been developed considering that the coherent integration durations are multiples of the PRN code duration and dividers of the data bit duration. However, it is also possible to choose durations that do not divide the data bit duration, such as 6 ms. In this case, the average probability of detection can be modeled based on the same theoretical methodology, however it is complex and we chose not to present it. Some elements to compute it are proposed using as an example a dwell time of 60 ms. Let us assume that there is a shift of 1 ms between the local and the incoming signal:

- There is a bit transition at $t_0 = 1$ ms during the first integration $[0,6]$ ms (data bit transition at 1 ms).
- There is a bit transition at $t_0 = 3$ ms during the fourth integration $[18, 24]$ ms (data bit transition at 21 ms).
- There is a bit transition at $t_0 = 5$ ms during the seventh integration $[36, 42]$ ms (data bit transition at 41 ms)

However, if there are two bit sign transitions, the average probability of detection is not the same if they occur at the first and the second bit transitions or at the first and the third bit transitions. The average probability of detection should then take into account all the potential combinations of the locations of bit sign transitions (which depend on the correlation intervals).

B. *Galileo E1 OS Signal*

1) *Acquisition of Data and Pilot Signal Method*

For weak signals with data and pilot components such as Galileo E1 OS, it is preferable to acquire both components to avoid a loss of 3 dB on the received C/N_0. An acquisition method consists of considering the two components separately [16, 17]. The data and pilot components of the received signal are thus correlated separately with the local spreading codes of the data and pilot components respectively.

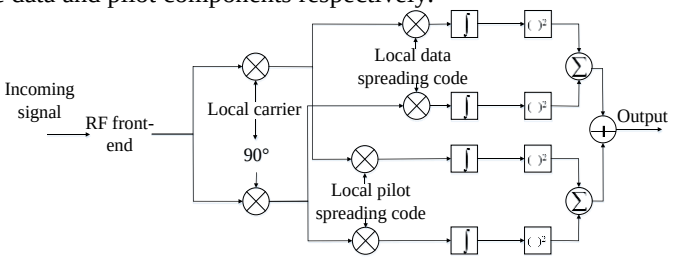


Fig. 10: Conceptual scheme of the data/pilot signal acquisition

The acquisition detector is then the sum of the two squared correlator outputs pairs corresponding to the data and pilot components as presented in Fig. 10.

$$T_{t_0} = \sum_{k=0}^{K} \frac{I_{t_0,Data}^2(k)}{\sigma^2} + \frac{Q_{t_0,Data}^2(k)}{\sigma^2} + \frac{I_{t_0,Pilot}^2(k)}{\sigma^2} + \frac{Q_{t_0,Pilot}^2(k)}{\sigma^2} \quad (32)$$

Assuming that the receiver uses the binary offset carrier BOC(1,1) local replica on the data and pilot components, there is no distinction between the data autocorrelation function and the pilot one for Galileo E1 OS. Moreover, the cross-correlation between the data and pilot spreading codes is assumed to be negligible because the choice of the spreading codes is as orthogonal as possible.

The duration of the spreading codes on Galileo E1 OS is equal to the duration of a data bit on the data component and to the duration of a secondary code bit on the pilot component. Therefore, a correlation duration equal to that of the spreading code period (4 ms) only is considered in this section.

2) *General Expression of the Probability of Detection for a Data/Pilot Signal*

From the described acquisition scheme, four correlator outputs have to be considered for the acquisition detector. This modifies the distribution of the acquisition detector: it remains a chi-square distribution, but with $4K$ degrees of freedom. From the Galileo E1 OS signal structure, a bit sign transition (the data bit for the data component and the secondary code for the pilot component) can occur at every spreading code period on the data and pilot components with a probability of 50%. Because the data bit duration is equal to the spreading code period (which implies $T_I = T_d$), the maximum number of bit sign transitions is $N_{max} = 2K$ ($\alpha = 0$). The probability of occurrence of n bit sign transitions can be modeled by a binomial distribution $\mathcal{B}(2K, 1/2)$ when K noncoherent summations are used. The general expression of the average probability of detection, given by (29), can be simplified for Galileo E1 OS as:

$$\forall K \in \mathbb{N}^*, \quad P_{d,t_0} = \frac{1}{2^{2K}} \sum_{n=0}^{2K} \binom{2K}{n} P_{d_{n,t_0}} \quad (33)$$

where $P_{d_{n,t_0}} = 1 - \mathcal{F}_{\chi^2(4K, n\times\lambda_{t_0} + (2K-n)\times\lambda_0)}(T_h)$

TABLE IV presents the optimal dwell time to reach a probability of detection equal or above 0.95 and at 27 dB-Hz when there is no Doppler and code delay residual error. This table shows that the effect of data bit transitions on the Galileo

E1 OS probability of detection is more pronounced than it is for GPS L1 C/A. This is because the correlation duration is constrained by the data bit rate, which is equal to the spreading code repetition rate. This means that on both the data and pilot channels, a sign transition can occur within each correlation interval.

TABLE IV
REQUIRED INTEGRATION TIME TO REACH A PROBABILITY OF DETECTION OF 95% (GALILEO E1 OS) WITH $\varepsilon_f = 0$ AND $\varepsilon_\tau = 0$

C/N_0 (dB-Hz)	No transition (ms)	Bit sign transition considered at worst location ($t_0 = T_I/2$) (ms)	Bit sign transition considered as random (ms)
25	172	580	436
26	116	388	292
27	80	264	200
28	56	180	136
29	40	128	96
30	28	92	68
31	20	64	48
32	16	48	36
33	12	36	28

As a consequence, in a general case, the optimal dwell time to reach an average probability of detection of 95% when considering bit sign transition is 2.5 times longer than when bit sign transitions are not considered. In the worst case, when the bit sign transition is in the middle of the coherent integration interval, the optimal dwell time is multiplied by around 3.3. These remarks highlight that the bit sign transition highly penalizes the acquisition of Galileo E1 OS if a specific countermeasure is not put in place. Even if such a countermeasure is used, the minimum dwell time to acquire a signal with C/N_0 lower than 30 dB-Hz is higher than that for GPS L1 C/A.

3) Probability of Detection Considering Bit Sign Transitions and Doppler and Code Delay Residual Errors

As previously done for GPS L1 C/A, the focus is now on the joint effect of bit sign transitions and Doppler and code delay residual errors for the acquisition of Galileo E1 OS components. Fig. 11 provides the probabilities of detection, for a C/N_0 of 27 dB-Hz and a dwell time of 200 ms, considering the ideal case in which there are no residual errors and there is the assumption of the absence of data (blue curve), considering residual errors on the frequency and time domain and absence of data (magenta curve) and finally the average probability of detection when considering bit sign transition and Doppler and code delay residual errors (red curve). As given in Table IV, at 27 dB-Hz, in 200 ms, the average probability of detection (only on the bit sign transition location) is 95 %. However, because of the strong of the acquisition cell size, it becomes 78 % when adding code delay and Doppler frequency residuals errors.

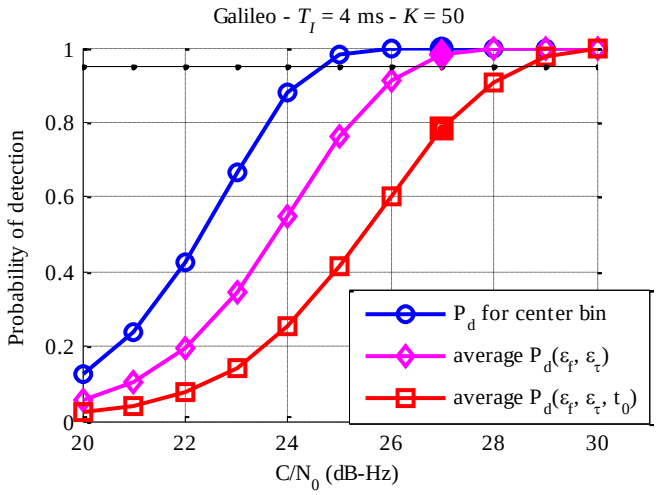


Fig. 11: Average probability of detection at 27 dB-Hz for Galileo E1 OS

These results clearly indicate the need for acquiring Galileo E1 OS at low C/N_0 meaning that a specific acquisition technique resistant to data bit transitions has to be used. For example [18] and [19] tackle the problem of the acquisition degradations because of bit sign transitions, at the expense of a higher complexity. In [18], a data bit transition insensitive variant of the Double Block Zero Padding acquisition method is developed, dedicated to the modernized GNSS signals. This method is based on partial correlations. If the local and incoming blocks are exactly synchronized but the incoming signal is affected by a bit sign transition, the previous results for GPS L1 C/A are still true. Thus, the longer the coherent integration time (which means the spreading code period), the better is the results.

CONCLUSIONS

In this paper, a mathematical study of the impact of bit sign transitions on the acquisition performance was presented. First, developing the acquisition detection problem, the probability of detection considering bit sign transitions was expressed. The main result is that the acquisition degradation is maximum for a bit sign transition in the center of the correlation interval. In a general way, even if the transition is not at the worst location, the acquisition losses are not negligible and should be taken into account, when choosing the acquisition parameters.

Second, we determined the average probability of detection taking into account the Doppler and code delay uncertainties linked to the size of the acquisition bins. A uniform distribution of all of these errors within the bin was considered. The same work was presented to evaluate the average probability of detection considering bit sign transitions assuming a uniform distribution of the location of the bit sign transition.

Finally, two test cases were proposed: GPS L1 C/A and Galileo E1 OS. The first one has a single component and the second one is composed of a data component and a pilot component with a 50 %/50 % power share. The mathematical development together with Monte-Carlo simulations showed that for the GPS L1 C/A signal, the optimal correlation time is generally 4 or 5 ms when considering the bit sign transitions, which allows good performance at high and low C/N_0 values.

Also, these simulations showed that the total dwell time required to reach a high probability of detection can be strongly underevaluated (typically by a factor of 2) if the bit sign transition is not considered, which is usually the case in publications.

The structure of the Galileo E1 OS signal (a spreading sequence with a duration equal to that of the bit duration) is clearly detrimental to the acquisition performance. Although this can appear as a significant performance drawback, it only means that the acquisition technique used by a Galileo E1 OS receiver should also be insensitive to data bit transitions, which usually implies a more demanding processing. Such methods have been proposed in the literature are [18, 19] .

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