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# GNSS Acquisition Thresholds for Civil Aviation GNSS Receivers

Guillaume Novella, Axel J. Garcia-Pena, Christophe Macabiau, Anaïs Martineau, *Ecole Nationale de l'Aviation Civile*  
Pierre Ladoux, Philippe Estival, Olivier Troubet-Lacoste, *Direction des Services de la Navigation Aérienne (DSNA)*

## Biographies

Guillaume NOVELLA graduated as a space and aeronautical telecommunications engineer from ENAC (Ecole Nationale de l'Aviation Civile) in 2019. He is now a Ph.D student at the TELECOM lab of the ENAC. His Ph.D topic deals with drone C2Link and GNSS operating margins.

Axel GARCIA-PENA is a researcher/lecturer with the SIGnal processing and NAVigation (SIGNAV) research axis of the TELECOM lab of ENAC (French Civil Aviation University), Toulouse, France. His research interests are GNSS navigation message demodulation, optimization and design, GNSS receiver design and GNSS satellite payload. He received his double engineer degree in 2006 in digital communications from SUPAERO and UPC, and his PhD in 2010 from the Department of Mathematics, Computer Science and Telecommunications of the INPT (Polytechnic National Institute of Toulouse), France.

Christophe MACABIAU graduated as an electronics engineer in 1992 from the ENAC (Ecole Nationale de l'Aviation Civile) in Toulouse, France. Since 1994, he has been working on the application of satellite navigation techniques to civil aviation. He received his Ph.D in 1997 and has been in charge of the signal processing lab of ENAC since 2000, where he also started dealing with navigation techniques for terrestrial navigation. He is currently the head of the TELECOM team of ENAC, that includes research groups on signal processing and navigation, electromagnetics, and data communication networks.

Anaïs MARTINEAU graduated in 2005 as an electronics engineer from the Ecole Nationale de l'Aviation Civile (ENAC) in Toulouse, France. She received her Ph.D. in 2008 from the University of Toulouse. She is now the Head of Electronics, Electromagnetism and Signal Processing Division of the ENAC.

Philippe ESTIVAL is a GNSS expert at the French civil aviation service provider (DGAC/DSNA/DTI) currently involved in EGNOS mission requirements and standardization activities on future multi-constellation GNSS receivers Eurocae WG62 and within EU/US cooperation agreement Working Group C. He has been in charge of CCF (EGNOS Central Control Facility) operational support and evolutions for PACF department until 2009 and then for ESSP SAS System Operation Unit up to 2015. He graduated in 2005 as an electronics engineer from French Civil Aviation University, Toulouse, France.

Pierre LADOUX started his career as maintenance engineer on conventional radionavigation aids and then was involved at DSNA/DTI, the French Air Navigation Provider Technical Directorate, in activities related to satellite navigation systems and more specifically on the ICAO standardized Ground Based Augmentation System (GBAS). He is now the head of the Spectrum and Frequency management unit at DSNA.

## Abstract

Civil aviation GNSS receiver must fulfill minimum requirements defined in standardization documents in order to be certified. International Civil Aviation Organization (ICAO) and Radio Technical Commission for Aeronautics (RTCA) GNSS receiver requirements on message demodulation, pseudorange accuracy and acquisition performance can be expressed as a function of signal carrier to noise power spectral density ratio ( $C/N_0$ ); where the minimum  $C/N_0$  allowing to meet the GNSS receiver required performance are called thresholds,  $C/N_{0,th}$ . In other words, received GNSS signal  $C/N_0$  is supposed to exceed particular  $C/N_0$  thresholds in order to guarantee that each basic operation of the GNSS receiver (acquisition, tracking, demodulation) meets its required performance; and civil aviation GNSS receiver manufacturers must guarantee the fulfillment of receiver requirements if the received signal  $C/N_0$  is equal to or above the associated requirement threshold.

Certification requirements for Dual Frequency Multi Constellations (DFMC) receivers, which are the new generation of civil aviation GNSS receivers, are currently being elaborated. The objective of this article is to revise and to adapt the calculation of the acquisition thresholds for DFMC GNSS receiver. This article starts by presenting acquisition requirements for the current civil aviation GNSS receiver generation (legacy receiver) and DFMC receiver. This article follows by describing the mathematical method used to derive the acquisition thresholds and by computing their numerical values for the different processed signals: GPS L1 C/A for the legacy receiver, GPS L1 C/A, Galileo E1, GPS L5 and Galileo E5a for DFMC receiver. Finally, this article establishes  $C/N_0$  link budgets for acquisition to verify that the received signal  $C/N_0$  is above  $C/N_0$  acquisition threshold at all points in the world, and therefore, that acquisition requirements can be met worldwide.

## 1 INTRODUCTION

GNSS is a Radio Navigation Satellite System (RNSS) which can be used as an Aeronautical Radio Navigation System (ARNS) for some carrier frequency signals. ARNS is by definition a Safety of Life (SoL) system. SoL systems are defined as radiocommunications services used for safeguarding human life and property (International Telecommunication Union, 2001). SoL systems have particular protections to ensure they do not suffer from harmful interference coming from other radiocommunication systems (ITU, 2020). In particular, a priority is given to SoL systems in terms of spectrum efficiency and robustness of system operation if a non-SoL system may create harmful interference. Another fundamental characteristic of SoL systems is the fulfillment of safety application-dependent specifications to become certified. Indeed, to be certified GNSS receiver must pass some tests demonstrating that their minimum performance is sufficient to achieve a given operation (requirement). Minimum performance and test procedures are described in certifications documents called Minimum Operational Performance Standard (MOPS).

The current generation of civil aviation GNSS receiver is referred as legacy GNSS receiver. This kind of receiver only uses GPS L1C/A signals to provide positioning and timing service. Its minimum performance is defined through the requirements listed in DO-229E (Radio Technical Commission for Aeronautics, 2016). Test procedures used to verify the GNSS receiver fulfillment of the requirements are also described in DO-229E. The derivation of the test procedures is based on analysis assessing the capability of the receiver to operate in the L1-band radio frequency interference (RFI) environment. This analysis is detailed in DO-235B (Radio Technical Commission for Aeronautics, 2008). In the coming years, a new generation of receiver is going to be used in civil aviation, referred as dual frequency multi-constellation receiver (DFMC). As a major difference with legacy receivers, DFMC receivers will be able to process GPS L5, Galileo E1 and Galileo E5a signals in addition to GPS L1C/A. Analysis of the capability of a DFMC receiver to operate in presence of RFI is developed in DO-235C (RTCA, 2022) for the L1/E1 GNSS frequency band RFI environment and in the future DO-292A (RTCA, 2004) for the L5/E5a GNSS frequency band RFI environment. Test procedures for DFMC will be developed in ED-259A (Eurocae, 2023), which is expected to be released by end 2023.

Minimum performance requirements of certification documents (ED-259 (Eurocae, 2023) for DFMC receiver, DO-229E (RTCA, 2016) for legacy receiver) can often be translated into a minimum carrier to noise power spectral density  $C/N_0$  requirement. In other words, minimum performance requirements for a given GNSS signal processing operation should be fulfilled if and only if the GNSS signal  $C/N_0$  exceeds a given threshold. Therefore, these thresholds are a major input to the RFI environment analysis.

Among the different signal processing operations performed by a GNSS receiver, acquisition consists in detecting the presence or absence of a GNSS signal coming from a given satellite. In case of a positive detection, the acquisition module must output a rough estimation of the code delay and Doppler frequency to initialize tracking loops. Therefore, the acquisition step contributes to the availability of the GNSS positioning and timing service. The acquisition thresholds are defined by the assumed minimum  $C/N_0$  values needed to fulfill time to first fix (TTFF) requirements.

As previously said, the calculation of the acquisition threshold has a major significance when assessing the capability of the receiver to meet minimum performance in a nominal RFI environment. As a matter of fact, these performance assessments are traditionally conducted by performing  $C/N_0$  link budget analysis in the nominal RFI environment.  $C/N_0$  link budget analysis consists in comparing the estimated received signal  $C/N_0$  in a given RFI environment to the  $C/N_0$  threshold for the considered GNSS receiver signal processing operation. A positive  $C/N_0$  link budget margin should be interpreted as the capability of the GNSS receiver to meet minimum requirements for the considered operation in the nominal RFI environment.

GPS L1C/A acquisition thresholds for legacy receiver are computed in DO235B (RTCA, 2008). GPS L1C/A acquisition thresholds are aligned with the legacy TTFF requirements. Acquisition thresholds for GPS L5 signals were derived in DO292 (RTCA, 2004)

and (C. Hegarty et al., 2003), in (Bastide et al., 2002) for Galileo E5a, and in (Julien et al., 2011) for Galileo E1. However, since TTFF requirements for DFMC receiver were not issued when these works were published, their assumptions are not aligned with the up-to-date requirements. The objective of this article is thus to provide acquisition thresholds in line with the new TTFF requirements of ED-259 (Eurocae, 2023), and to demonstrate the capability of the DFMC GNSS receiver to meet TTFF requirements under nominal RFI conditions described in DO-235C (RTCA, 2022) for L1-band and DO-292 (RTCA, 2004) for L5-band.

In order to achieve these objectives, this article is divided in three main sections. First, DFMC TTFF requirements are presented and analyzed. From this analysis, a simple strategy to get a first fix is proposed, and the main inputs to acquisition threshold calculation are determined. Although not optimal, this strategy will be compliant with the TTFF requirements and sets a “minimum” strategy which can be adopted to fulfill the requirements. Second, the mathematical approach to derive acquisition thresholds is presented. Acquisition process is conducted at the correlator output. Therefore, this section starts by proposing a mathematical model for the correlator outputs of the different GNSS signals. This section follows by developing the mathematical equations leading to the acquisition thresholds. Third, the capability of the receiver to respect TTFF requirements is analyzed, showing that the  $C/N_0$  link budget margin is positive at all points in the world.

## 2 DFMC TTFF REQUIREMENTS

The objective of this section is to present and to analyze TTFF requirements for DFMC receivers in order to propose some inputs needed to compute acquisition thresholds. DFMC TTFF requirements are first introduced and discussed. Second, a DFMC acquisition strategy compliant with the requirements is described in order to propose additional inputs needed to the acquisition threshold derivation.

### 2.1 Presentation of DFMC TTFF requirements

Three different DFMC TTFF requirements are analyzed here.

#### DMS:306:

The equipment shall output a valid position within 5 minutes with a 95% probability of success after power application given the following conditions:

- Latitude and longitude initialized within 60 nautical miles;
- Time and date initialized within 1 minute;
- Valid GPS and GAL almanac data available and unobstructed satellite visibility;
- Under Normal Acquisition Interference Conditions;
- GPS and GAL signals from Minimum Signal Conditions to Maximum Signal Conditions;
- Valid ionospheric data available.

This requirement is very similar to the legacy TTFF requirement, for which a valid position shall be output with 95% probability of success using GPS L1C/A signals only. The difference with legacy TTFF requirement is the availability of Galileo signals.

#### DMS:199:

The equipment shall output a valid SBAS L5 augmented position within 15 minutes with a 95% probability of success after power application given the following conditions:

- Latitude and longitude initialized within 60 nautical miles;
- Time and date initialized within 1 minute;
- Valid GPS, GAL, and SBAS almanac data and unobstructed satellite visibility;
- Under Normal Acquisition Interference Conditions;
- GPS and GAL signals from Minimum Signal Conditions to Maximum Signal Conditions;
- At least one SBAS L5 signal (PRN code) at Minimum Signal Conditions, without the associated SBAS L1 signal (same PRN code), broadcasting messages augmenting GPS only.

## DMS:210:

The equipment shall output a valid SBAS L5 augmented position within 15 minutes with a 95% probability of success after power application given the following conditions:

- Latitude and longitude initialized within 60 nautical miles;
- Time and date initialized within 1 minute;
- Valid GPS, GAL, and SBAS almanac data and unobstructed satellite visibility;
- Under Normal Acquisition Interference Conditions;
- GPS and GAL signals from Minimum Signal Conditions to Maximum Signal Conditions;
- At least one SBAS L5 signal (PRN code) at Minimum Signal Conditions, without the associated SBAS L1 signal (same PRN code), broadcasting messages augmenting Galileo only.

DMS:199 and DMS:210 are equivalent and request a DFMC navigation solution. The difference between these two requirements is the constellation augmented by the Satellite Based Augmentation System (SBAS). Indeed, in DMS:199, GPS signals are augmented by the SBAS, whereas Galileo signals are augmented by SBAS in DMS:210.

Conditions associated to the TTFF requirements can be interpreted as follows. First, the position and time are roughly known. This estimation of the time and position helps the positioning algorithm to output a more precise navigation position in a limited time, since it limits the number of Doppler bins in the estimation matrix. Second, almanacs are supposed to be known and an open sky configuration is considered. This condition is important. Indeed, it may help the acquisition process since signals can be acquired in a decreasing elevation order, or from the highest  $C/N_0$  value to the lowest value. Third, normal acquisition interference conditions are defined in ED-259 (Eurocae, 2023). As part of GNSS receiver testing, interferences are considered by injecting additional average white gaussian noise (AWGN) into the receiver. Therefore, the interference increases the noise floor term  $N_0$ . The noise power spectral density is part of the acquisition threshold, so this condition does not impact the calculation of the acquisition threshold but rather the definition of the associated certification test. Fourth, GNSS signals are assumed to be from minimum to maximum signal conditions. Signal conditions are defined in ED-259 in terms of minimum and maximum GNSS signal power at the antenna port. Similar to the previous condition, the GNSS signal power is part of the acquisition threshold, so this condition does not impact the calculation of noise condition but rather the certification test derivation. Fifth, DMS:306 supposes the knowledge of valid ionospheric data. This assumption is important to perform integrity monitoring with receiver autonomous integrity monitoring (RAIM) in order to ensure that the output position is valid. However, it does not impact the calculation of the acquisition threshold. Sixth and last, DMS:199 and DMS:210 specifies the settings for SBAS satellite generation. More precisions are given in ED-259.

## **2.2 Acquisition strategy compliant with TTFF requirements**

An acquisition strategy, compliant with requirements presented in section 2.1, is presented here. From the strategy, some inputs to the acquisition threshold derivation are proposed. These inputs are:

- Allocated time to acquire each signal: At least four signals are needed to fulfill DMS:306, whereas at least nine signals are needed to fulfill DMS:199 (four GPS L1C/A signals, four GPS L5 signals, and one SBAS L5 signal) and DMS:210 (four Galileo E1 signals, four Galileo E5a signals, and one SBAS L5 signal). The sum of the allocated times for each signal should not exceed the TTFF: 5 min for DMS:306, 15 min for DMS:210 and DMS:199.
- Probability of successful acquisition of each signal: The probability of successful acquisition of a given signal is the probability to detect the signal, knowing it is in view, within the allocated time. Considering that the successive acquisitions are independent from each other, the probability of TTFF success is the product of the probability of successful acquisition of each targeted individual signal. According to the requirements, the probability of TTFF success must be higher than 0.95.

This section is divided in four paragraphs. First, for each pair of constellation and frequency band, a duration is allocated to compute a navigation solution. Second, calculation of a first fix for a given constellation and frequency is further analyzed in order to propose an allocated time to acquire each individual signal. Third, the probability of successful acquisition for individual GNSS signal is proposed. Fourth, a verification that the time to perform DFMC acquisition does not exceed the TTFF for each requirement is done.

### **2.2.1 Time allocation for each system**

The proposed allocated time to perform a first fix for each pair of constellation and frequency band are summarized in TABLE 1. Acquisition, tracking and demodulation of at least four signals of a given system must be performed during the associated allocated

time. Note that at least 5 min are required to download the SBAS message. An extra 1 min is added to perform the acquisition of the SBAS signal.

TABLE 1  
Proposed Allocated Time to Perform a First Fix for Each Pair of Constellation and Frequency Band

Signal	GPS		Galileo		SBAS acquisition and demodulation
	L1C/A	L5	E1	E5	L5
Allocated time	5 min	5 min	6.5 min	5 min	6 min

### 2.2.2 Time allocation for each signal

The calculation of a first fix for a given core constellation and frequency is performed in three steps.

- **Step 1:** A first GNSS signal is acquired. Once the first space vehicle (SV) is acquired, the receiver clock can be synchronized with the first acquired GNSS signal. Therefore, the receiver clock contribution to Doppler uncertainty is removed for the acquisition of subsequent satellites, leading to a smaller Doppler space search.
- **Step 2:** Subsequent signals are acquired.
- **Step 3:** Additional operations necessary to compute a first fix are performed. These operations include the launching of the tracking loops, the removal of false detection (a false detection consists in detecting a signal even though the searched GNSS signal is not present), demodulation of navigation message, and integrity monitoring to ensure the validity of the output position. This step allows to guarantee the validity of the first fix, thanks to the time allocation for integrity processing and signal demodulation.

For the different pairs of constellation/frequency bands, proposed allocated time for each step is indicated in TABLE 2.

TABLE 2  
Sharing of the Allocated Time Between the Different First Fix Computation Steps

		Time allocated to 1 <sup>st</sup> SV acquisition (s)	Time allocated to each of the 2 <sup>nd</sup> , 3 <sup>rd</sup> and 4 <sup>th</sup> SV acquisition (s)	Time allocated to Step 3: Demodulation, integrity, verification, ... (s)	Total TTF (min)
GPS	L1C/A	60	30	150*	5
	L5	60	30	150*	5
Galileo	E1	96	48	150*	6.5
	E5a	60	30	150*	5

\*150s allocated to demodulation, integrity and verification is set on DO-235C (RTCA, 2022) and on DO-292 (RTCA, 2004).

Note that in DMS:199 and DMS:210, the second systems computing a first fix may take advantage of the first fix computed by the first system; in other words, GPS may profit from the first fix obtained from Galileo and the other way around. This benefit is not considered in this paper. Instead, acquisition thresholds are computed so that each system can perform a standalone acquisition (under conditions detailed in the requirements).

### 2.2.3 Probability of successful acquisition of a single satellite signal

Assuming that the acquisition of each individual SV is independent from the other, the probability of successful acquisition of a given satellite signal is given by Equation (1).

$$P_{success} = \prod_{i=1}^{N_{acq}} P_{acq,i} \quad (1)$$

Where  $P_{acq,i}$  is the probability of successfully acquiring SV  $i$  in the allocated time, and  $N_{acq}$  is the total number of SVs to be acquire in order to comply with TTFF requirements.

TTFF requirements impose  $P_{success} = 0.95$ . In addition, to fulfill DMS:306,  $N_{acq} = 4$  SVs are needed, whereas  $N_{acq} = 9$  SVs are needed to fulfill DMS:210 and DMS:199. The most constraining requirements in terms of probability of success are clearly DMS:199 and DMS:210. In this paper, it is proposed to set  $P_{acq,i}$  to the same value for all satellites. Therefore, the probability to successfully acquire SV  $i$  is given by Equation (2) (with  $N_{acq} = 9$ ).

$$P_{acq} = P_{acq,i} = (P_{success})^{\frac{1}{N_{acq}}} \quad (2)$$

In this article,  $P_{acq}$  is rounded up to 0.995.

#### 2.2.4 Compliance with TTFF requirements

In this section, the compliance of the proposed time allocation with the TTFF requirements is investigated.

##### Compliance with DMS:306

In DMS:306, 5 Galileo and 5 GPS signals, on both the L1/E1 and L5/E5a frequency bands, are supposed to be available. Since 5 min are allocated to compute a first fix with GPS L1C/A signal, and since the probability of successful acquisition is  $(P_{acq})^4 = 0.98 > 0.95$ , then this requirement is fulfilled.

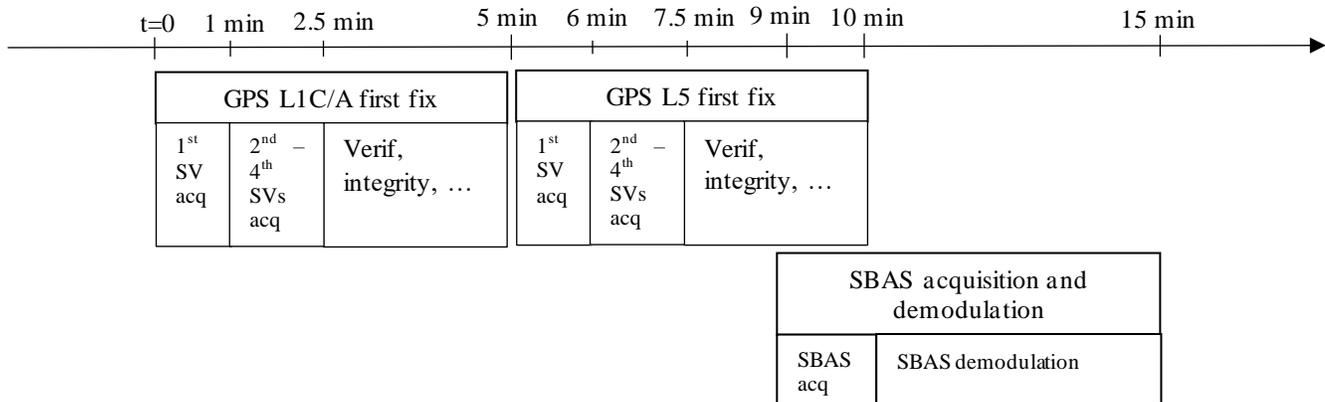
##### Compliance with DMS:199

To fulfill requirement DMS:199, the receiver must perform three operations: calculation of a first fix with GPS L1C/A signals, calculation of a first fix with GPS L5 and to acquire and demodulate SBAS signal in order to augment the GPS navigation solution. Clearly, from the time allocation presented in TABLE 1, these three operations cannot be performed successively without exceeding the total acquisition time of DMS:199 (15 min).

Therefore, to be compliant with DMS:199, DFMC first fix operations can take place in that order.

- 1) Between  $t=0$  s and  $t=5$  min, the receiver computes a first fix with GPS L1C/A signals.
- 2) Between  $t=5$  min and  $t=10$  min, the receiver computes a first fix with GPS L5 signals.
- 3) In parallel of the previous action, the receiver acquires and demodulates SBAS signal between  $t=9$  min and  $t=15$  min.

**Figure 1** illustrates this dual frequency GPS acquisition process.



**Figure 1** GPS Acquisition Strategy Compliant with DMS:199

The limiting resource when computing a first fix is the number of correlators. In this article, correlator is complex, meaning that one correlator output corresponds to a pair of in-phase and quadrature phase correlator outputs. The availability of a high number of correlators is necessary to perform acquisition of GNSS signals. Conversely, once a GNSS signal is acquired, only a few correlators are required to track the GNSS signal and to perform demodulation, verification, and integrity monitoring. From **Figure 1**, even though the SBAS acquisition and demodulation step starts in parallel of GPS L5 first fix step, SBAS signal acquisition is initiated

after that GPS L5 signals have been acquired. As a consequence, the acquisition strategy presented here should not be over-demanding in terms of number of correlators.

In addition, the probability to successfully meet TTFF requirement is  $(P_{acq})^9 = 0.995^9 > 0.95$ . Therefore, this DFMC acquisition strategy is compliant with DMS:199.

#### Compliance with DMS:210

To fulfill DMS:210, the receiver must perform three operations: calculation of a first fix with Galileo E1 signals, calculation of a first fix with Galileo E5a signal, and acquisition and demodulation of SBAS signal in order to augment Galileo navigation solution.

To be compliant with DMS:210, it is proposed that DFMC acquisition operations take place in that order:

- 1) Between  $t=0$  s and  $t=6.5$  min, the receiver computes a first fix with Galileo signals.
- 2) Between  $t=6.5$  min and  $t=11.5$  min, the receiver computes a first fix with Galileo E5a signals.
- 3) In parallel of the previous action, the receiver acquires and demodulates SBAS signal between  $t=9$  min and  $t=15$  min.

Figure 2 illustrates this dual frequency Galileo acquisition process.

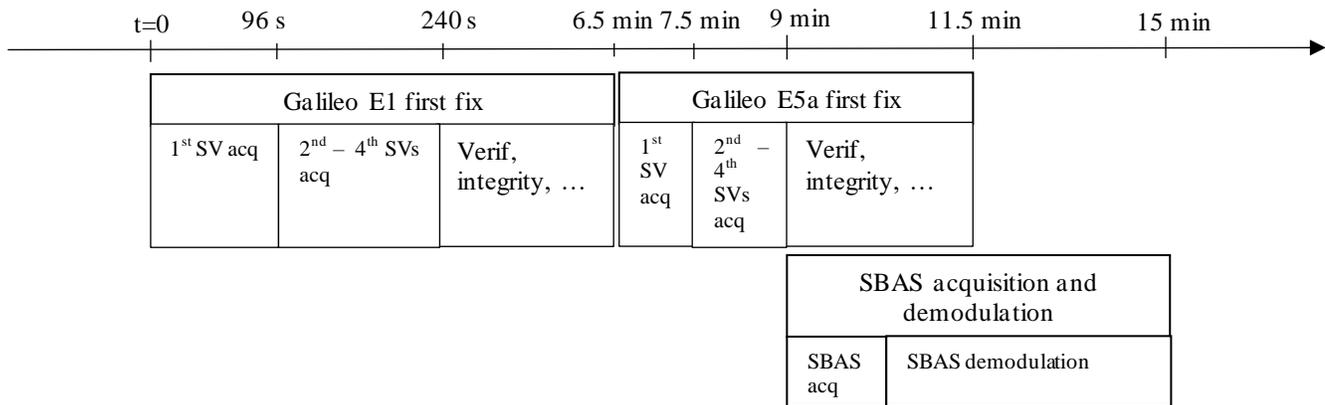


Figure 2 Galileo Acquisition Strategy Compliant with DMS:210

With this strategy, SBAS signal acquisition begins after Galileo E5a signals acquisition ends. Consequently, this strategy should not be over-demanding in terms of number of correlators as already argued for DMS:199 requirement.

In addition, the probability to successfully meet TTFF requirement is  $(P_{acq})^9 = 0.995^9 > 95\%$ . Therefore, this DFMC acquisition strategy is compliant with DMS:210.

### 3 ACQUISITION THRESHOLDS DERIVATION

The goal of this section is to derive the acquisition thresholds of DFMC receivers for up to date ED259 requirements. This section is divided in four parts. First, since acquisition is conducted at the GNSS receiver correlators output, a mathematical model of the GNSS signals correlator output is presented. Second, the definition of the signal power used in the acquisition threshold derivation is presented. Third, the method to acquire each satellite is described. This method, which may be not optimal, has the advantage of being quite simple. Fourth, the mathematical derivation of acquisition threshold is detailed, and the results are presented.

#### 3.1 GNSS signal correlator output model

(Van Dierendonck, 1995) models the GPS L1C/A signal at the correlator output at epoch  $k$  as

$$\begin{aligned}
I_{L1}^D(k) &= \sqrt{\frac{P_{L1}}{2}} d(k) \tilde{R}_{c_D, c_D}^{L1}(\varepsilon_\tau) \text{sinc}(\pi \varepsilon_f T_i) \cos(\varepsilon_\phi) + n_{I, L1}(k) \\
Q_{L1}^D(k) &= \sqrt{\frac{P_{L1}}{2}} d(k) \tilde{R}_{c_D, c_D}^{L1}(\varepsilon_\tau) \text{sinc}(\pi \varepsilon_f T_i) \sin(\varepsilon_\phi) + n_{Q, L1}(k)
\end{aligned} \tag{3}$$

- $P_{L1}$  is the GPS L1C/A signal power at the antenna port. Cable losses as well as various losses due to signal distortion by the transmitter or propagation channel are assumed to be contained within this term.
- $d$  is the bit of the navigation message.
- $\tilde{R}_{c_D, c_D}^{L1}$  is the cross-correlation function between the filtered GPS L1C/A pseudo-random noise (PRN) code and the PRN signal used for the local replica.
- $T_i$  is the coherent integration time.
- $\varepsilon_\tau, \varepsilon_f$  and  $\varepsilon_\phi$  are respectively the difference of code delay, frequency and phase between the receiver GNSS signal and the estimations used to generate the local replica.
- $n_{I, L1}$  and  $n_{Q, L1}$  are AWGN samples, which power is  $\sigma_n^2 = \frac{\beta N_0}{4T_i}$ .  $N_0$  is the noise power spectral density at RFFE output, and  $\beta$  traduces the impact of the RFFE equivalent filter and correlation on the noise. Denoting  $H_{RF, BB}$  the RFFE filter transfer function at baseband, and  $S_{c_m}$  the power spectral density of the local replica,  $\beta$  can be expressed by Equation (4).

$$\beta = \int_{-\infty}^{+\infty} |H_{RF, BB}(f)|^2 S_{c_m}(f) df \tag{4}$$

GPS L5 and Galileo E5a signals are different from GPS L1C/A signal since they have two components, called data and pilot. Each component is in quadrature-phase from each other. GPS L5 and Galileo E5a are both BPSK chip modulated with the same chip rate and, although the PRN code data rate is 10 times higher for GPS L5 and Galileo E5a than for GPS L1C/A, they still have a similar mathematical expression in terms of mathematical model. Therefore, a common correlator output mathematical model is provided, and common acquisition thresholds will be derived as well. (Macabiau et al., 2003) models the correlator output of the pilot and data components of Galileo E5a and GPS L5 signals as in Equation (5).

$$\begin{aligned}
I_{L5 E5a}^D(k) &= \sqrt{\frac{P_{L5}}{4}} \left( d(k) h_{10}(k) \tilde{R}_{c_D, c_D}^{L5 E5a}(\varepsilon_\tau) + h_{20}(k) \tilde{R}_{c_P, c_D}^{L5 E5a}(\varepsilon_\tau) \right) \text{sinc}(\pi \varepsilon_f T_i) \cos(\varepsilon_\phi) + n_{I, L5}^D(k) \\
Q_{L5 E5a}^D(k) &= \sqrt{\frac{P_{L5}}{4}} \left( d(k) h_{10}(k) \tilde{R}_{c_D, c_D}^{L5 E5a}(\varepsilon_\tau) + h_{20}(k) \tilde{R}_{c_P, c_D}^{L5 E5a}(\varepsilon_\tau) \right) \text{sinc}(\pi \varepsilon_f T_i) \sin(\varepsilon_\phi) + n_{Q, L5}^D(k) \\
I_{L5 E5a}^P(k) &= \sqrt{\frac{P_{L5}}{4}} \left( d(k) h_{10}(k) \tilde{R}_{c_D, c_P}^{L5 E5a}(\varepsilon_\tau) + h_{20}(k) \tilde{R}_{c_P, c_P}^{L5 E5a}(\varepsilon_\tau) \right) \text{sinc}(\pi \varepsilon_f T_i) \cos(\varepsilon_\phi) + n_{I, L5}^P(k) \\
Q_{L5 E5a}^P(k) &= \sqrt{\frac{P_{L5}}{4}} \left( d(k) h_{10}(k) \tilde{R}_{c_D, c_P}^{L5 E5a}(\varepsilon_\tau) + h_{20}(k) \tilde{R}_{c_P, c_P}^{L5 E5a}(\varepsilon_\tau) \right) \text{sinc}(\pi \varepsilon_f T_i) \sin(\varepsilon_\phi) + n_{Q, L5}^P(k)
\end{aligned} \tag{5}$$

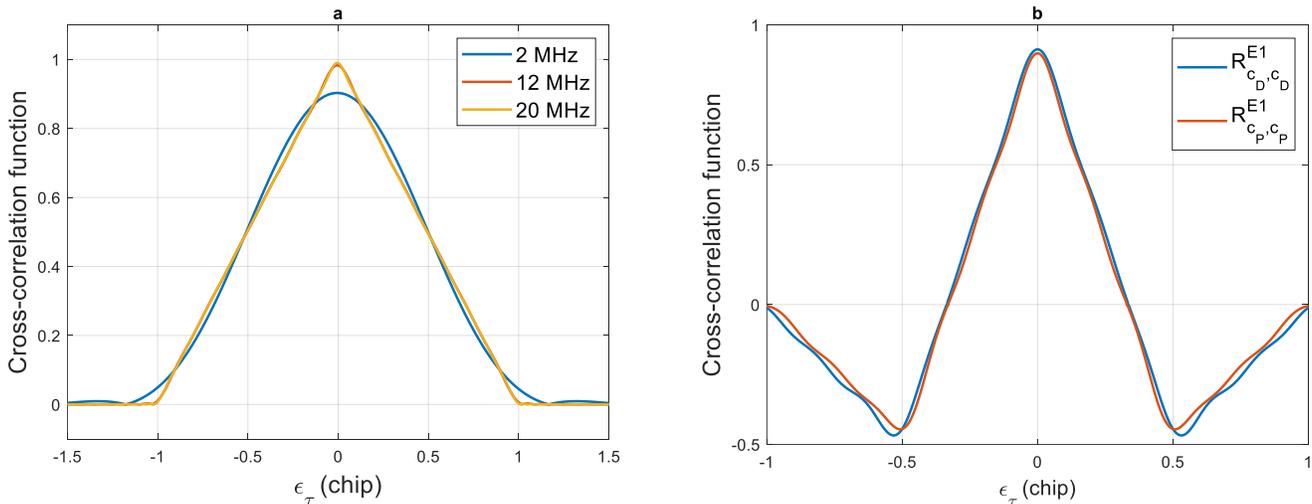
- $P_{L5}$  is the total GNSS power (data plus pilot components power) at the antenna port.
- $h_{10}$  is the bit of the data component secondary code.
- $h_{20}$  is the bit of the pilot component secondary code.
- $\tilde{R}_{X, Y}^{L5 E5a}$  is the cross-correlation function between the received filtered PRN signal  $X$  and the local replica  $Y$ . Since data and pilot use the same modulation, BPSK(10), then  $\tilde{R}_{c_D, c_D}^{L5 E5a} = \tilde{R}_{c_P, c_P}^{L5 E5a}$ . Note that in reality Galileo E5A does not implement a BPSK(10) modulation for the data and pilot components since the signal really implements the AltBOC modulation; nevertheless, the approximation is very tight for the purposes of this work.
- $n_{I, L5}^D, n_{Q, L5}^D, n_{I, L5}^P$  and  $n_{Q, L5}^P$  are independent AWGN samples with power  $\sigma_n^2$  (different value from GPS L1 C/A due to the customization of the  $\beta$  term).

Galileo E1 signal also have one pilot and one data component. The main differences with GPS L5 and Galileo E5a signal are a different chip modulation, the absence of the secondary code on the data component and a shorter PRN code (but longer than for GPS L1 C/A). (Julien et al., 2011) models the data and pilot correlator outputs as in Equation (6).

$$\begin{aligned}
 I_{E1}^D(k) &= \sqrt{\frac{P_{E1}}{4}} \left( d(k) \tilde{R}_{c_D, c_D}^{E1}(\epsilon_\tau) - s_c(k) \tilde{R}_{c_P, c_D}^{E1}(\epsilon_\tau) \right) \text{sinc}(\pi \epsilon_f T_i) \cos(\epsilon_\varphi) + n_{I, E1}^D(k) \\
 Q_{E1}^D(k) &= \sqrt{\frac{P_{E1}}{4}} \left( d(k) \tilde{R}_{c_D, c_D}^{E1}(\epsilon_\tau) - s_c(k) \tilde{R}_{c_P, c_D}^{E1}(\epsilon_\tau) \right) \text{sinc}(\pi \epsilon_f T_i) \sin(\epsilon_\varphi) + n_{Q, E1}^D(k) \\
 I_{E1}^P(k) &= \sqrt{\frac{P_{E1}}{4}} \left( -d(k) \tilde{R}_{c_D, c_P}^{E1}(\epsilon_\tau) + s_c(k) \tilde{R}_{c_P, c_P}^{E1}(\epsilon_\tau) \right) \text{sinc}(\pi \epsilon_f T_i) \cos(\epsilon_\varphi) + n_{I, E1}^P(k) \\
 Q_{E1}^P(k) &= \sqrt{\frac{P_{E1}}{4}} \left( -d(k) \tilde{R}_{c_D, c_P}^{E1}(\epsilon_\tau) + s_c(k) \tilde{R}_{c_P, c_P}^{E1}(\epsilon_\tau) \right) \text{sinc}(\pi \epsilon_f T_i) \sin(\epsilon_\varphi) + n_{Q, E1}^P(k)
 \end{aligned} \tag{6}$$

- $P_{E1}$  is the total Galileo E1 power (data plus pilot components power) at the antenna port.
- $s_c$  is the Galileo E1 secondary code of the pilot component.
- $\tilde{R}_{X,Y}^{E1}$  is the cross-correlation function between the received filtered Galileo E1 PRN signal  $X$  and the local replica  $Y$ . In this paper, the local replica is  $BOC(1,1)$  modulated whereas the received data and pilot components have respectively a  $CBOC(6,1,1/11,+)$  and  $CBOC(6,1,1/11,-)$  modulations. This mismatch between the received signal, which is in addition distorted by RFFE filter, and local replica induces some additional losses dependent on the receiver bandwidth.
- $n_{I, E1}^D, n_{Q, E1}^D, n_{I, E1}^P$  and  $n_{Q, E1}^P$  are independent AWGN samples with power  $\sigma_n^2$ .

It can be seen from Equations (4), (5) and (6) that the RFFE filter plays a role on the correlation functions of the different received signals with the corresponding local replica. **Figure 3-a** represents this cross-correlation function between the received filter signal and the local replica, when the GNSS signal is GPS L1C/A. **Figure 3-b** represents the cross-correlation functions between the received filtered Galileo E1 components (data and pilot) and a  $BOC(1;1)$  local replica when the RFFE filter double-sided bandwidth is set to 12 MHz (minimum receiver bandwidth allowed for Galileo E1 receiver in ED-259).



**Figure 3** Impact of RFFE bandwidth on correlation function

**Figure 3** shows that the RFFE bandwidth, as well as the mismatch of the local replica with the Galileo E1 signal, induces a loss of GNSS signal power. Indeed, the peak of the correlation function does not reach 1. This loss of power grows along the RFFE bandwidth decreases.

### 3.2 Signal power definition

The received signal power at the antenna port is also impacted by other stages of the GNSS receiver. The recovered signal power designates the GNSS signal power which is in reality processed by the signal processing module. It includes filtering signal losses, as well as some signal losses which may occur within the receiver. This new definition of the GNSS signal power is considered when deriving  $C/N_0$  acquisition threshold.

The RFFE filter and correlation also plays a role on the filtering of the noise as previously said and modelled in the  $\beta$  term. Therefore, the total impact of the RFFE filter and of the correlation, on both the GNSS signal power and noise band-limiting, is characterized by the band-limiting and mismatch term loss defined by Equation (7) for GPS L5, Galileo E5a and Galileo E1 (where  $X$  is either L5 E5a or E1), and by Equation (8) for GPS L1C/A.

$$L_m^X = \frac{\tilde{R}_{c_D,c_D}^X(0)^2 + \tilde{R}_{c_P,c_P}^X(0)^2}{2\beta} \quad (7)$$

$$L_m^{L1} = \frac{R_c^{L1}(0)^2}{\beta} \quad (8)$$

Figure 4 shows the evolution of band-limiting and mismatch term losses as a function of the RFFE bandwidth.

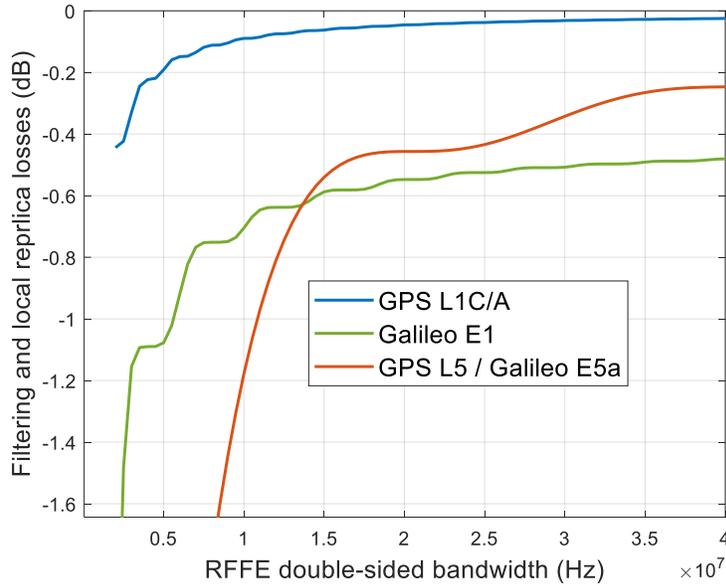


Figure 4 Band-limiting and local replica mismatch losses as a function of double-sided RFFE bandwidth

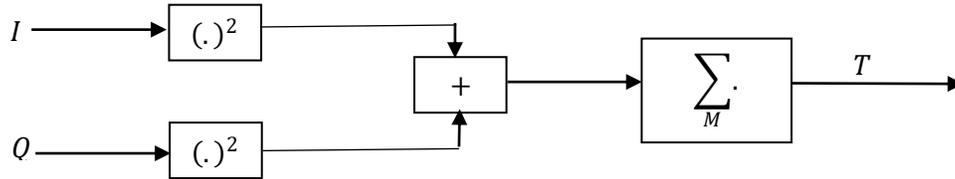
Legacy receiver bandwidth is within the range [2 MHz; 20 MHz], whereas DFMC receiver bandwidth is between 12 MHz and 24 MHz. Therefore, RFFE filtering and mismatch of the local replica with the GNSS signal induce a non-negligible loss on the recovered signal power. To take into account this loss, it is more suitable to define the recovered signal power  $C_X$  instead of working with the power at the antenna port  $P_X$ , where  $X$  denotes the type of GNSS signal.

$$C_X = L_m^X P_X \quad (9)$$

### 3.3 Acquisition description

The acquisition process is based on computing power samples at the correlator output. More specifically, the acquisition detector is built adding successive correlator output power samples and using this detector to decide whether the targeted signal is present or not with the signal characteristics used to compute the correlator outputs; usually, this decision is taken by comparing the detector to a threshold. Indeed, the power at the correlator output is significant only if code delay and Doppler frequency of the local replica are close to those of the received signal (and if the local replica PRN code corresponds to the received signal PRN code). Therefore, the

acquisition is performed by using an acquisition matrix as a support. Each cell of the acquisition matrix represents a pair of Doppler frequency and code delay values, respectively defined over intervals  $F$  (total frequency range) and  $D$  (total delay range). For each cell representing a different Doppler frequency and code delay value, the acquisition detector is usually compared to a threshold: if the acquisition detector exceeds the threshold, then a signal is detected, and the verification phase is launched to check if this detection is a false alarm or not. If the acquisition detector is below the threshold, then no GNSS signal is detected on that cell, and the acquisition process moves to the next cell. For a single GNSS component signal such as GPS L1C/A, a potential acquisition detector is shown in **Figure 5**.



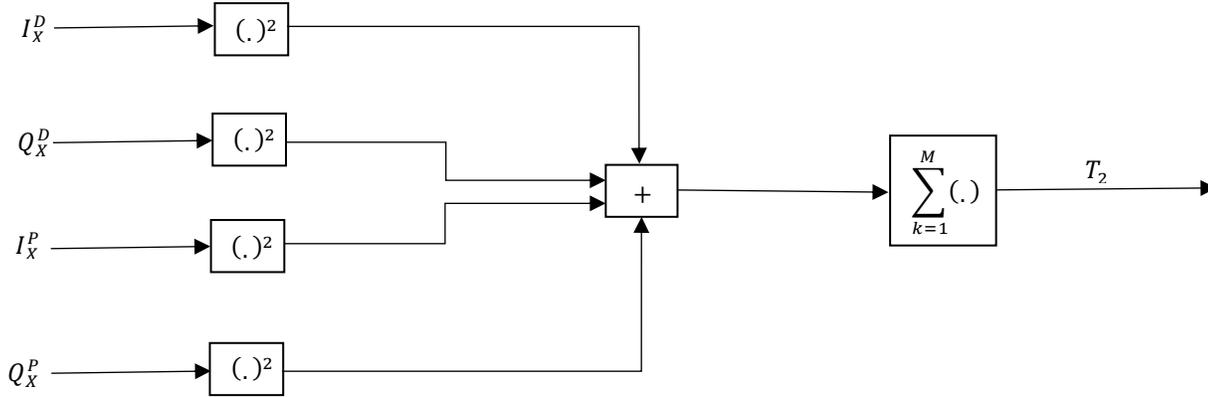
**Figure 5** One GNSS component acquisition detector

The acquisition detector associated to **Figure 5** is mathematically defined by Equation (10).

$$T_1 = \sum_{k=1}^M (I_{L1}^D(k))^2 + (Q_{L1}^D(k))^2 \quad (10)$$

$M$  is the number of non-coherent summations.

When a pilot component is available, the acquisition may take benefit of this second GNSS component. In this case, an alternative acquisition detector can be built from the correlator outputs of both the pilot and data components, as shown in **Figure 6**.



**Figure 6** Acquisition detector for two components GNSS signal

The acquisition detector represented in **Figure 6** can be mathematically expressed by Equation (11).

$$T_2 = \sum_{k=1}^M (I_x^D(k))^2 + (Q_x^D(k))^2 + (I_x^P(k))^2 + (Q_x^P(k))^2 \quad (11)$$

$X$  is the GNSS signal with a data and a pilot component, either Galileo E1, GPS L5 or Galileo E5a.

### 3.4 Acquisition thresholds derivation

This section presents the mathematical derivation of the acquisition thresholds associated to the acquisition detectors presented in section 3.3. This section is divided in three parts. First, the main inputs for this calculation are reminded. Second, a mathematical expression of the acquisition threshold is proposed. Third, acquisition thresholds are computed and discussed.

#### 3.4.1 Inputs for acquisition thresholds calculation

Settings that are necessary to derive acquisition thresholds value include:

- Allocated time to acquire each satellite  $T_{acq,i}$   
 $T_{acq,i}$  with  $i \in \llbracket 1; 4 \rrbracket$ , is the allocated time to acquire the  $i^{\text{th}}$  SV, and is presented in TABLE 2.
- Probability of successful acquisition of a signal  $P_{acq}$   
 $P_{acq}$  is set to 0.995 for each GNSS signal, according to section 2.2.3.
- Uncertainty on the Doppler frequency  
Considering uncertainties due to user dynamics, almanac, date and receiver clock drift, DO-292 (RTCA, 2004) estimated the total uncertainty on velocity at 51 m/s for en-route operations and 300 m/s for ground acquisition, when no clock synchronization were assumed. These velocity uncertainties can be translated into frequency uncertainties summarized in TABLE 3. Once the first SV has been acquired, receiver clock can synchronize with the GNSS signal, so the frequency uncertainty significantly drops for the acquisition of subsequent SVs.

TABLE 3  
Doppler uncertainty for the different GNSS signals

		En-route operations	On the ground operations
Doppler uncertainty on L1/E1 frequency band (Hz)	1 <sup>st</sup> SV acquisition	$F = \pm 268 \text{ Hz}$	$F = \pm 1500 \text{ Hz}$
	2 <sup>nd</sup> – 4 <sup>th</sup> SV acquisition	$F = \pm 150 \text{ Hz}$	$F = \pm 150 \text{ Hz}$
Doppler uncertainty on L5/E5a frequency band (Hz)	1 <sup>st</sup> SV acquisition	$F = \pm 200 \text{ Hz}$	$F = \pm 1200 \text{ Hz}$
	2 <sup>nd</sup> – 4 <sup>th</sup> SV acquisition	$F = \pm 120 \text{ Hz}$	$F = \pm 120 \text{ Hz}$

Note that the Doppler uncertainties values that have been used in previous acquisition thresholds derivations were on-ground frequency uncertainty for the L1/E1 band, and en-route frequency uncertainty value for L5/E5a signal. In this paper, and to consider a worst case, on-ground frequency uncertainty value for L5/E5a signal will be considered as well.

- Uncertainty on the GNSS signal code delay  
The uncertainty on the code delay is linked with the length of the PRN code. GPS L1C/A codes is 1023 chips long, Galileo E1 PRN codes are 4092 chips long and GPS L5 and Galileo E5a codes are 10230 chips long. For GPS L1C/A and Galileo E1, the code delay must be searched browsing the whole PRN code length, for the first and subsequent SVs acquisition. Concerning GPS L5 and Galileo E5a, the whole PRN code must be browsed as well for first SV acquisition. However, after having acquired the first SV, code delay uncertainty may be decreased according to (RTCA, 2004) to 7570 chips. TABLE 4 recaps the code delay uncertainty for the different GNSS signals to acquire.

TABLE 4  
Code delay uncertainty for the different GNSS to acquire

		Code delay uncertainty
GPS L1C/A	1 <sup>st</sup> SV acquisition	$D = \pm 1023 \text{ chips}$
	2 <sup>nd</sup> – 4 <sup>th</sup> SV acquisition	$D = \pm 1023 \text{ chips}$
Galileo E1	1 <sup>st</sup> SV acquisition	$D = \pm 4092 \text{ chips}$
	2 <sup>nd</sup> – 4 <sup>th</sup> SV acquisition	$D = \pm 4092 \text{ chips}$
GPS L5/Galileo E5a	1 SV acquisition	$D = \pm 10230 \text{ chips}$
	2 <sup>nd</sup> – 4 <sup>th</sup> SV acquisition	$D = \pm 7570 \text{ chips}$

- Number of cells in the acquisition matrix  
The number of cells in the acquisition matrix can be mathematically expressed by Equation (12).

$$N_{tot} = L \times H \quad (12)$$

$$L = \left\lceil \frac{D}{\delta d} \right\rceil \quad H = \left\lceil \frac{F}{\delta f} \right\rceil$$

$\delta d$  is the width of one code delay bin, and  $\delta f$  is the width of one frequency bin.  $\lceil . \rceil$  is the ceiling operator.

The settings for  $\delta d$  and  $\delta f$  depend on the maximum acceptable loss of GNSS signal power due to imperfect synchronization of the local replica with the GNSS received signal. Indeed, the maximum synchronization errors due code delay and frequency imperfect synchronization are respectively  $\delta d/2$  and  $\delta f/2$ . The associated loss of GNSS signal power,

respectively denoted  $\Delta C_d$  (loss of power due to imperfect code delay synchronization) and  $\Delta C_f$  (loss of power due to imperfect frequency synchronization), are given in Equation (13).

$$\Delta C_d = \left( \frac{\bar{R}_x^Y \left( \frac{\delta d}{2} \right)}{\bar{R}_x^Y(0)} \right)^2 \quad \Delta C_f = \text{sinc}^2 \left( \pi \frac{\delta f}{2} T_i \right) \quad (13)$$

Where  $T_i$  is the integration time. Acquisition is usually performed by coherent integrating (correlation duration) over one PRN sequence to avoid finding navigation and secondary code bit transition inside the integration. Therefore, in this article,  $T_i = 1 \text{ ms}$  when acquiring GPS L1C/A, GPS L5 and Galileo E5a signals and  $T_i = 4 \text{ ms}$  for Galileo E1 SV acquisition. In the literature (Bastide et al., 2002) (Julien et al., 2011),  $\delta f$  is often set to  $\frac{1}{2T_i}$ , resulting in a maximum power loss because of frequency miss-synchronization  $\Delta C_f = -0.9 \text{ dB}$ . This setting is also adopted in this article.

The code delay is linked to the shape of the cross-correlation function. (RTCA, 2008) sets the size of a code delay cell width,  $\delta$ , to half a chip, so that the loss due to code delay miss-synchronization  $\Delta C_d$  does not exceed -2.6 dB (for an infinite RFFE filter bandwidth).

Concerning Galileo E1 signal, **Figure 3** shows that the slope of the correlation function is around three times higher than the slope of the GPS correlation function. Therefore, (Julien et al., 2011) proposes to divide by three the code delay cell width compared to the GPS case. Adopting this setting,  $\delta d = \frac{1}{6} T_{chip}$ , where  $T_{chip}$  is the chip period.

TABLE 5 summarizes the number of cells in the acquisition matrix.

TABLE 5  
Size of the acquisition matrix for the different signals to acquire

		Code delay uncertainty $D$	Code delay cell width $\delta d$	Number of code delay cells $L$	Frequency uncertainty $F$	Frequency cell width $\delta f$	Number of frequency cells $H$	Total number of cells $N_{tot}$
<b>GPS L1C/A</b>	1 <sup>st</sup> SV acquisition	1023 chips	$\frac{1}{2}$ chip	2046	3000 Hz	500 Hz	6	<b>12276</b>
	2 <sup>nd</sup> – 4 <sup>th</sup> SV acquisition	1023 chips	$\frac{1}{2}$ chip	2046	300 Hz	500 Hz	1	<b>2046</b>
<b>Galileo E1</b>	1 <sup>st</sup> SV acquisition	4092 chips	$\frac{1}{6}$ chip	24552	3000 Hz	125 Hz	24	<b>589248</b>
	2 <sup>nd</sup> – 4 <sup>th</sup> SV acquisition	4092 chips	$\frac{1}{6}$ chip	24552	300 Hz	125 Hz	3	<b>73656</b>
<b>GPS L5/Galileo E5a</b>	1 <sup>st</sup> SV acquisition	10230 chips	$\frac{1}{2}$ chip	20460	2400 Hz	500 Hz	5	<b>102300</b>
	2 <sup>nd</sup> – 4 <sup>th</sup> SV acquisition	7570 chips	$\frac{1}{2}$ chip	15140	240 Hz	500 Hz	1	<b>15140</b>

Note the size of the acquisition matrix for the acquisition of the first Galileo E1 SV is much higher than for the other signals. This is mainly due to the lower frequency and code delay cell widths.

- Probability of false alarm  $P_{fa}$

$P_{fa}$  is the probability to detect a GNSS signal in a given cell when the signal is not there, either because the satellite is not in view or because the cell's Doppler and code delay values of the local replica do not correspond to the Doppler and code delay values of the received GNSS signal. The probability of false alarm is set in order to limit the number of false detections while browsing the whole acquisition matrix.

The probability of false alarm is set in DO-235B (RTCA, 2008) to  $10^{-3}$ . The mean value of false detections, browsing the entire acquisition matrix, is then  $N_{tot} P_{fa}$ . Note that for GPS L1C/A 1<sup>st</sup> SV acquisition, the average number of false detections is higher than 12. To have few false detections is not a problem since the verification process described in section 2.2.2 aims to detect and remove the false detections. This false alarm value for GPS L1C/A is re-used in this article as an input for acquisition threshold calculation.

For GPS L5 and Galileo E5a, DO-292 proposes to set  $P_{fa}$  to  $10^{-4}$  following a simple reasoning. Indeed, since there are 10 times more code delay cells in GPS L5/Galileo E5a acquisition matrix than in GPS L1C/A acquisition matrix and since the number of frequency cells is lower for GPS L5/Galileo E5a than for GPS L1C/A, to set  $P_{fa}$  to  $10^{-4}$  does not increase the average number of false detections. This  $P_{fa}$  value is used for GPS L5/Galileo E5a acquisition in this article.

A finer apportionment is done for Galileo E1. Indeed,  $P_{fa}$  is set so that the average number of false detections in Galileo E1 acquisition matrix is the same than in GPS L1C/A acquisition matrix. The probability of false detections, for 1<sup>st</sup> Galileo E1 SV acquisition and subsequent Galileo E1 SVs acquisition, is thus given by Equation (14).

$$\begin{aligned} P_{fa,1}^{E1} &= \frac{N_{tot,1}^{L1}}{N_{tot,1}^{E1}} P_{fa}^{L1} \\ P_{fa,2}^{E1} &= \frac{N_{tot,2}^{L1}}{N_{tot,2}^{E1}} P_{fa}^{L1} \end{aligned} \quad (14)$$

Where  $N_{tot,i}^X$  is the number of cells in the acquisition matrix of the first ( $i = 1$ ) or subsequent ( $i = 2$ ) SV of system  $X$ . Values for  $N_{tot,i}^X$  can be extracted from TABLE 5.  $P_{fa}^{L1}$  is the probability of false detection for GPS L1C/A acquisition. Probabilities of false detection for the different systems and SVs to be acquired are recapped in TABLE 6.

TABLE 6  
Probabilities of false detection for the different signals to acquire

		Probability of false detection $P_{fa}$
GPS L1C/A	1 <sup>st</sup> SV acquisition	$10^{-3}$
	2 <sup>nd</sup> – 4 <sup>th</sup> SV acquisition	$10^{-3}$
Galileo E1	1 <sup>st</sup> SV acquisition	$2.08 \cdot 10^{-5}$
	2 <sup>nd</sup> – 4 <sup>th</sup> SV acquisition	$2.78 \cdot 10^{-5}$
GPS L5/Galileo E5a	1 <sup>st</sup> SV acquisition	$10^{-4}$
	2 <sup>nd</sup> – 4 <sup>th</sup> SV acquisition	$10^{-4}$

Because of the higher number of cells in Galileo E1 acquisition matrix compared to GPS L1C/A,  $P_{fa}$  must be lower for Galileo E1 to maintain the same average number of false detections when the whole acquisition matrix is browsed.

- Number of complex correlators  $N_{corr}$

The number of correlators is a key parameter in the calculation of the acquisition thresholds. In this article, correlators are considered as complex, thus one correlator output refers to a pair of one in-phase and one quadrature phase correlator outputs. However, there is no requirement on that point. Thus, receiver manufacturers can decide the number of implemented correlators allocated to acquisition. Instead of speculating on the number of correlators used by the receiver, this article provides the acquisition threshold as a function of the number of correlators allocated to the acquisition process.

These inputs allow to compute the number of non-coherent summations on each cell of the acquisition matrix. The number of non-coherent summations is limited by the maximum time to acquire each satellite  $T_{acq,i}$ , the number of correlators  $N_{corr}$  and by the number of cells in the acquisition matrix. Also, it depends on the acquisition detector which is used. Indeed, acquisition detector  $T_2$  needs correlator outputs of the pilot and data components whereas acquisition detector  $T_1$  only needs the correlator outputs of the data component. Therefore, the number of correlators can be mathematically expressed by Equation (15).

$$M_{T_1} = \left\lfloor \frac{N_{corr} T_{acq,i}}{N_{tot} T_i} \right\rfloor \quad M_{T_2} = \left\lfloor \frac{N_{corr} T_{acq,i}}{2N_{tot} T_i} \right\rfloor \quad (15)$$

$\lfloor \cdot \rfloor$  is the floor operator. The time spent on one cell is  $MT_i$  and is called the dwell time. From the inputs presented in this section, acquisition thresholds can now be computed.

### 3.4.2 Theoretical acquisition threshold derivation

This section provides a mathematical expression for the acquisition thresholds. The acquisition method presented in this article is based on a Neyman-Pearson detection test. One potential acquisition detector has been presented in section 3.3 for each signal:  $T_1$  for GPS L1C/A and  $T_2$  for Galileo E1, Galileo E5a and GPS L5 signals. This section is divided in three parts. First, the probability distribution of the selected acquisition detectors under null and alternative ( $H_0$  and  $H_1$ ) Neyman Pearson hypothesis is analyzed. Second, the probability of detection is determined as a function of the GNSS signal  $C/N_0$ . Third, acquisition thresholds are derived.

#### Distribution of acquisition detector under hypothesis $H_0$ and $H_1$

##### Null hypothesis $H_0$ :

Under null hypothesis  $H_0$ , the searched GNSS signal is not present. However, another GNSS signal, different from the searched one, is assumed to be present, leading to the presence of a cross-correlation term.  $\varepsilon_{\tau,max}$  and  $\varepsilon_{f,max}$  refers to code and Doppler estimation errors leading to the highest cross-correlation  $\varepsilon_{f,max} = 0$  in the worst-case scenario so that the interfering GNSS signal induces the maximum cross-correlation. Under hypothesis  $H_0$ , the acquisition detector  $T_1$  presented in Equation (10) can be reduced as in Equation (16) for GPS L1C/A

$$T_1 = \sum_{k=1}^{MT_1} \left[ \left( \sqrt{\frac{P_J}{2}} d(k) \tilde{R}_{cD,J,cD}^{L1}(\varepsilon_{\tau,max}) \cos(\varepsilon_{\varphi}) + n_{I,L1}^D \right)^2 + \left( \sqrt{\frac{P_J}{2}} d(k) \tilde{R}_{cD,J,cD}^{L1}(\varepsilon_{\tau,max}) \sin(\varepsilon_{\varphi}) + n_{Q,L1}^D \right)^2 \right] \quad (16)$$

$\tilde{R}_{cD,J,cD}^X$  and  $\tilde{R}_{cP,J,cD}^X$  are the cross-correlation functions between the data and pilot PRN codes with the data PRN code of signal  $X$ .  $P_J$  is the total power of the interfering GNSS signal.

$T_1$  can be normalized by the noise power  $\sigma_n^2$  so that the normalized acquisition detector  $\bar{T}_1$  follows a non-central Chi-square distribution with  $2MT_1$  degrees of freedom. The non-centrality parameter is given by Equation (17) for GPS L1C/A.

$$\lambda_0^{T_1} = \frac{P_J}{2\sigma_n^2} \sum_{k=1}^{MT_1} \tilde{R}_{cD,J,cD}^X(0)^2 = \frac{2T_1}{\beta N_0} P_J M_{T_1} \tilde{R}_{cD,J,cD}^X(\varepsilon_{\tau,max})^2 = 2T_i \frac{C_J}{N_0} M_{T_1} K_J^{T_1} \quad (17)$$

$$K_J^{T_1} = \frac{\tilde{R}_{cD,J,cD}^X(\varepsilon_{\tau,max})^2}{\tilde{R}_{cD,J,cD,J}^X(0)^2}$$

Similarly, and assuming that the contribution of navigation bits and secondary codes are random, uncorrelated and with zero-mean, it can be shown that the normalized acquisition detector  $\bar{T}_2 = T_2/\sigma_n^2$  follows a non-centered Chi-square distribution with  $4M_{T_2}$  degrees of freedom and non-centrality parameter given by Equation (18).

$$\lambda_0^{T_2} = 2T_i \frac{C_J}{N_0} M_{T_2} K_J^{T_2} \quad (18)$$

$$K_J^{T_2} = \frac{\left( \tilde{R}_{cD,J,cD}^X(\varepsilon_{\tau,max})^2 + \tilde{R}_{cP,J,cD}^X(\varepsilon_{\tau,max})^2 + \tilde{R}_{cD,J,cP}^X(\varepsilon_{\tau,max})^2 + \tilde{R}_{cP,J,cP}^X(\varepsilon_{\tau,max})^2 \right)}{\tilde{R}_{cD,J,cD,J}^X(0)^2 + \tilde{R}_{cP,J,cP,J}^X(0)^2}$$

$K_J^{T_l}$ , with  $l \in \{1; 2\}$ , is the cross-correlation between the interfering signal PRN code and the PRN code of the local replica. The cross-correlation level between two different PRN codes depends mainly on the length of one PRN code. Consistently with the values proposed in (RTCA, 2022), (RTCA, 2004) and (Julien et al., 2011), the values used in this article for  $K_J^{T_1}$  and  $K_J^{T_2}$  are recapped in TABLE 7.

TABLE 7 Cross-correlation interference

	GPS L1C/A	Galileo E1	GPS L5 / Galileo E5a
Cross-correlation $K_j^{T_l}$	-24 dB	-29.5 dB	-34 dB

$\frac{C_l}{N_0}$  is set to 50 dB-Hz for all kinds of signal.

**Alternative hypothesis  $H_1$ :**

Under alternative hypothesis  $H_1$ , the searched signal is supposed to be present which means the pair of Doppler frequency and code delay of the cell being tested correspond to the Doppler frequency and code delay of the received signal. In this case, thanks to the correlation properties between PRN codes of the same satellite signal, it can be assumed  $\tilde{R}_{c_D, c_P}^X(\varepsilon_\tau) \ll \tilde{R}_{c_D, c_D}^X(\varepsilon_\tau)$  and  $\tilde{R}_{c_P, c_D}^X(\varepsilon_\tau) \ll \tilde{R}_{c_P, c_P}^X(\varepsilon_\tau)$ .

Under hypothesis  $H_1$ , the normalized acquisition detector  $\bar{T}_1$  follows a non-centered Chi-square distribution with  $2M_{T_1}$  degrees of freedom. In this case, the amplitude of other satellites signals at the correlator output area assumed to be much lower than the amplitude of the targeted signal and thus they are neglected. The non-centrality parameter is given in Equation (19).

$$\lambda_1^{T_1} = \sum_{k=1}^{M_{T_1}} \frac{P_{L1}}{2\sigma_n^2} \tilde{R}_{c_D, c_D}^{L1}(\varepsilon_\tau)^2 \text{sinc}^2(\pi \cdot \varepsilon_f \cdot T_i) \quad (19)$$

In addition,  $\varepsilon_\tau$  and  $\varepsilon_f$  can be considered as constant over the dwell time. Therefore, Equation (19) can be reduced to

$$\lambda_1^{T_1} = 2M_{T_1} T_i \frac{C_{L1}}{N_0} \left( \frac{\tilde{R}_{c_D, c_D}^{L1}(\varepsilon_\tau)}{\tilde{R}_{c_D, c_D}^{L1}(0)} \right)^2 \text{sinc}^2(\pi \cdot \varepsilon_f \cdot T_i) \quad (20)$$

Likewise, the normalized acquisition detector  $\bar{T}_2$  follows a Chi-square distribution with  $4M_{T_2}$  degrees of freedom. The non-centrality parameter is given in Equation (21).

$$\lambda_1^{T_2} = 2M_{T_2} T_i \frac{C_X \tilde{R}_{c_D, c_D}^X(\varepsilon_\tau)^2 + \tilde{R}_{c_P, c_P}^X(\varepsilon_\tau)^2}{N_0 \tilde{R}_{c_D, c_D}^X(0)^2 + \tilde{R}_{c_P, c_P}^X(0)^2} \text{sinc}^2(\pi \cdot \varepsilon_f \cdot T_i) \quad (21)$$

**Probability of detection**

Knowing the distribution of the acquisition detectors under hypothesis  $H_0$  and  $H_1$ , it is possible to compute the probability of detection,  $P_{md}$ , as a function of the GNSS signal  $C_X/N_0$ , where  $X$  is the GNSS signal of interest. The probability of detection is calculated in two steps. First, the detection threshold is set to respect the false alarm probability. Second, the probability of detection, which is the probability that the acquisition detector exceeds the threshold in presence of the GNSS signal, is computed.

1<sup>st</sup> Step: The detection threshold  $T_h^l, l \in \{1; 2\}$ , is defined from the distribution of the acquisition detector  $T_l$  and on the probability of false alarm  $P_{fa}$  (see section 3.4.1).  $T_h^l, l \in \{1; 2\}$  is derived from fundamentelequation (22).

$$\mathbb{P}(T_l > T_h^l | H_0) = P_{fa} \quad (22)$$

It has been seen that under hypothesis  $H_0, T_l/\sigma_n^2$  follows a Chi-square distribution with  $2lM_{T_l}$  degrees of freedom and non-centrality parameter  $\lambda_0^{T_l}$ . Therefore, the detection threshold can be mathematically expressed by Equation (23).

$$T_h = \sigma_n^2 F_{X^2}^{-1} \left( 1 - P_{fa} \right)_{2lM, \lambda_0^{T_l}} \quad (23)$$

$F_{X^2, \lambda}$  is the cumulative density function of a Chi square distribution with  $K$  degrees of freedom and non-centrality parameter  $\lambda$ . As an important remark, the detection threshold does not depend on the characteristics of the searched GNSS signal, in particular its  $C/N_0$ .

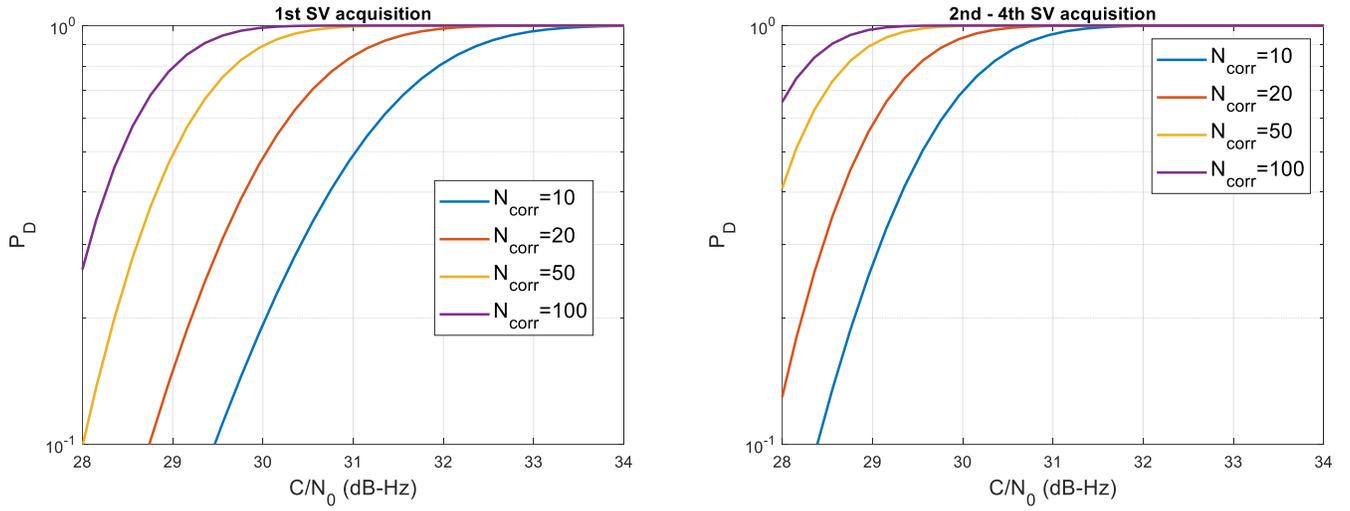
2<sup>nd</sup> step: Under hypothesis  $H_1, T_l/\sigma_n^2$  follows a Chi-square distribution with  $2lM_{T_l}$  degrees of freedom and non-centrality parameter  $\lambda_1^{T_l}$ . Note that  $\lambda_1^{T_l}$  depends on the  $C/N_0$  of the searched GNSS signal. In addition,  $\lambda_1^{T_l}$  also depends on the synchronization errors  $\varepsilon_\tau$  and  $\varepsilon_f$ . The probability of detection, considering  $\varepsilon_\tau$  and  $\varepsilon_f$  at fixed values, is given by Equation (24).

$$P_d \left( \frac{C}{N_0}, \varepsilon_\tau, \varepsilon_f \right) = \mathbb{P}(T_l \geq T_h | H_1) = 1 - F_{X_{2lM_{T_l}, \lambda_1^{T_l}}} \left( \frac{T_h}{\sigma_n^2} \right) \quad (24)$$

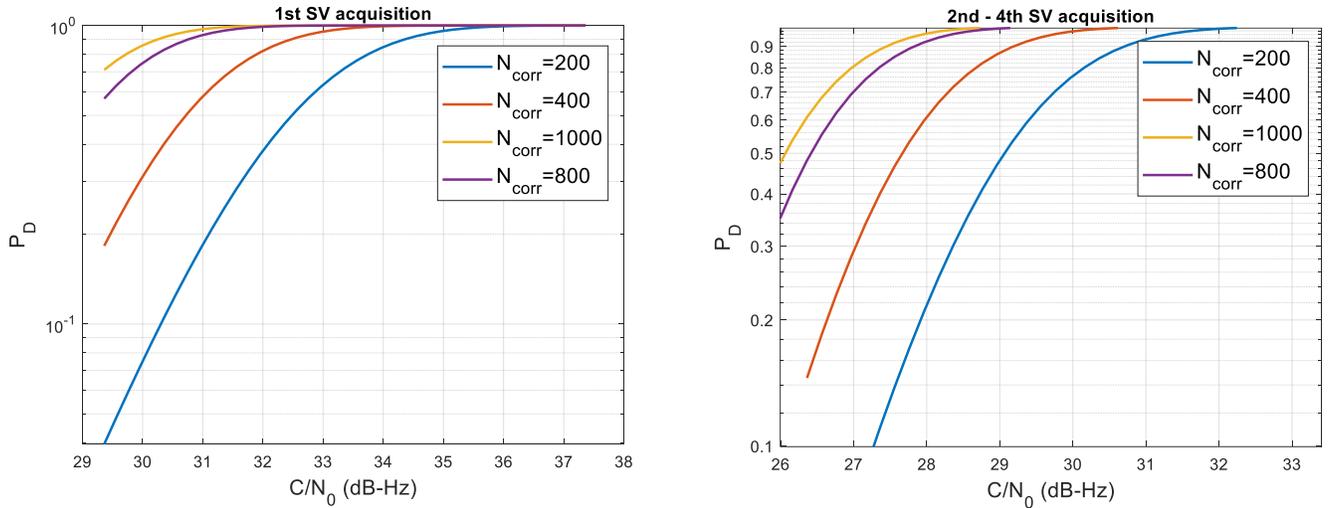
Eventually,  $\varepsilon_\tau$  and  $\varepsilon_f$  can be considered as random variables uniformly distributed over  $\left[-\frac{\delta d}{2}; \frac{\delta d}{2}\right]$  and  $\left[-\frac{\delta f}{2}; \frac{\delta f}{2}\right]$ . The average probability of detection is given by Equation (25).

$$P_D \left( \frac{C}{N_0} \right) = \mathbb{E} \left( P_d \left( \frac{C}{N_0}, \varepsilon_\tau, \varepsilon_f \right) \right), \varepsilon_\tau \hookrightarrow \mathbf{u} \left( \left[ -\frac{\delta d}{2}; \frac{\delta d}{2} \right] \right), \varepsilon_f \hookrightarrow \mathbf{u} \left( \left[ -\frac{\delta f}{2}; \frac{\delta f}{2} \right] \right) \quad (25)$$

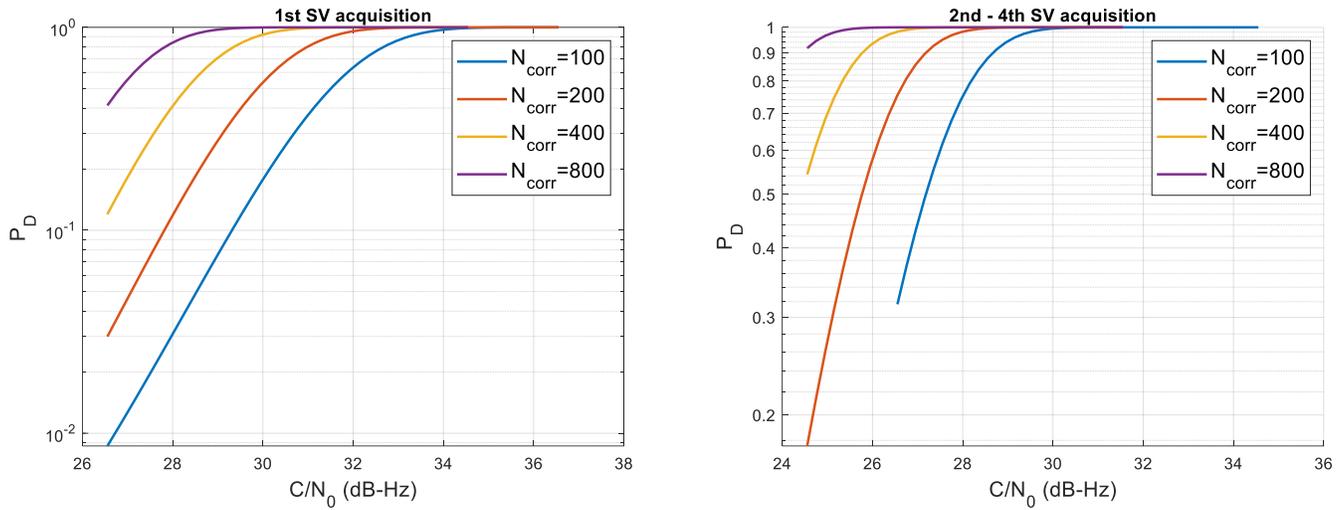
**Figure 7**, **Figure 8** and **Figure 9** represents the evolution of  $P_D \left( \frac{C}{N_0} \right)$  as a function of  $C/N_0$  for the different SVs to respectively acquire GPS L1C/A, Galileo E1 and GPS L5 / Galileo E5a signals. Several numbers of correlators are considered. The RFFE bandwidth is set to 2 MHz for GPS L1C/A, to 12 MHz for Galileo E1, and to 20 MHz for GPS L5 and Galileo E5a.



**Figure 7** Probability of detection for GPS L1C/A SVs



**Figure 8** Probability of detection for Galileo E1 SVs



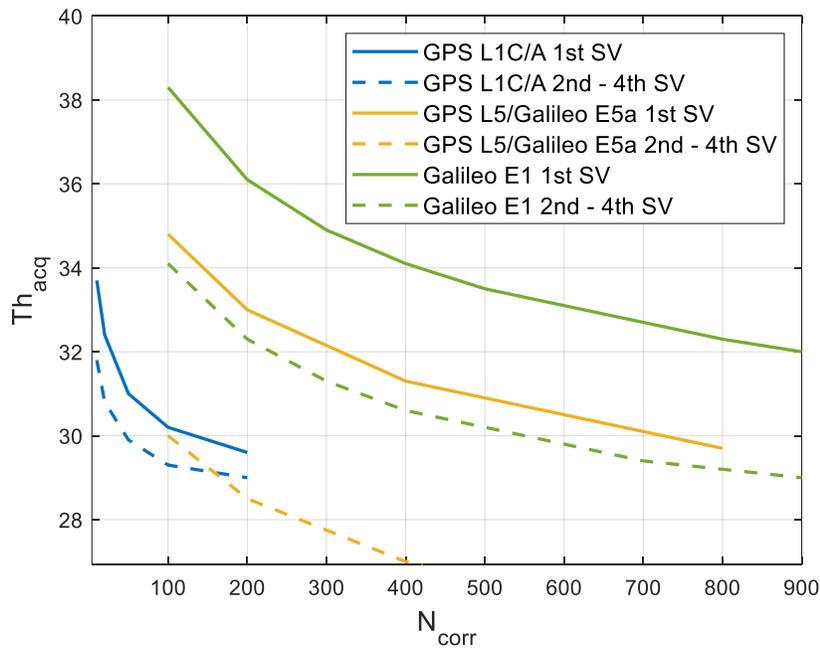
**Figure 9** Probability of detection for GPS L5 and Galileo E5a SVs

### Acquisition thresholds

The acquisition threshold is the minimum  $C/N_0$  value such that the average probability of detection  $P_D\left(\frac{C}{N_0}\right)$  exceeds the probability of successful acquisition of a signal  $P_{acq}$ . Acquisition threshold is given by Equation (26).

$$Th_{acq} = \min\left(\frac{C}{N_0} \mid P_D\left(\frac{C}{N_0}\right) \geq 0.995\right) \quad (26)$$

**Figure 10** represents the acquisition thresholds for the different signals to be acquired as part of the first fix determination, as a function of the number of correlators allocated to the acquisition  $N_{corr}$ .



**Figure 10** Acquisition thresholds

The highest acquisition thresholds, for both the first SV acquisition and subsequent SVs acquisition, concerns Galileo E1 signal. This observation is mainly due to the high number of cells in the Galileo E1 acquisition matrix (see TABLE 5).

Acquisition thresholds identified in certification documents DO-235C and DO-292 to assess the acquisition performance of GPS L1C/A, Galileo E1, GPS L5 and Galileo E5a are summarized in TABLE 8.

TABLE 8  
Acquisition thresholds identified by standardization

	GPS L1C/A		Galileo E1		GPS L5/Galileo E5a	
	1 <sup>st</sup> SV acquisition	2 <sup>nd</sup> – 4 <sup>th</sup> SV acquisition	1 <sup>st</sup> SV acquisition	2 <sup>nd</sup> – 4 <sup>th</sup> SV acquisition	1 <sup>st</sup> SV acquisition	2 <sup>nd</sup> – 4 <sup>th</sup> SV acquisition
Number of correlators $N_{corr}$	20	10	400	400	200	200
Acquisition threshold $Th_{acq}$	32.4	31.7	34.1	30.6	33	28.5

The number of correlators is low for GPS L1C/A, as the analysis of GPS L1C/A acquisition thresholds has first been conducted for GPS L1C/A legacy receiver in late 90's. The capacity of these receiver in terms on correlator number was lower than the current receivers. In addition, as GPS L1C/A acquisition thresholds are quite favorable, there is no need to review this assumption on the number of correlators. Because of acquisition thresholds for Galileo E1, Galileo E5a and GPS L5 are much higher, there is a need to consider a higher number of correlators in standardization document in order to limit the acquisition threshold. However, the number of complex correlators is easily achievable by current GNSS receivers.

#### 4 ASSESSMENT OF ACQUISITION PERFORMANCE

This section demonstrates that under nominal RFI environment conditions, carrier to effective noise ratio is above the acquisition threshold. The objective is to demonstrate that TTFF requirements are met in this nominal RFI environment, and therefore, to perform acquisition performance assessment. This section is divided in three parts. First, the definition of carrier to effective noise power spectral density  $C/N_{0,eff}$  is given as the carrier to noise power spectral density ratio in presence of RFI. Second, the nominal RFI environments, on both the L1/E1 and L5/E5a bands, are described. Third, the  $C/N_0$  link budget margin, defined as the difference (in dB) between the  $C/N_{0,eff}$  and the acquisition thresholds, is calculated. This third part shows that the  $C/N_0$  link budget margin is positive.

##### 4.1 Definition of carrier to effective noise power spectral density

This section defines the carrier to effective noise power spectral density in presence of RFI. The RFI impact on a GNSS receiver in civil aviation is usually modelled as the  $C/N_0$  degradation observed at the receiver's correlator output, or equivalently, as an increase of the effective  $N_0$  denoted as  $N_{0,eff}$ . This section is divided in two parts. First, assumptions on the GNSS recovered power  $C$  are recalled. Second, impact of RFI on noise power spectral density is modelled.

##### 4.1.1 GNSS recovered power

GNSS recovered power  $C$  is defined by Equation (27).

$$C = P_{GNSS} G_{ant} L_{imp} \quad (27)$$

Where:

- $P_{GNSS}$  is the received power at the Earth surface. Minimum received power at the earth surface for each system is specified by ICAO Standards and Recommended Practices (SARPS) (ICAO, 2006).  $P_{GNSS}$  values for GPS L1C/A, Galileo E1, GPS L5 and Galileo E5a are summarized in TABLE 9.

TABLE 9 Minimum GNSS received power at Earth surface

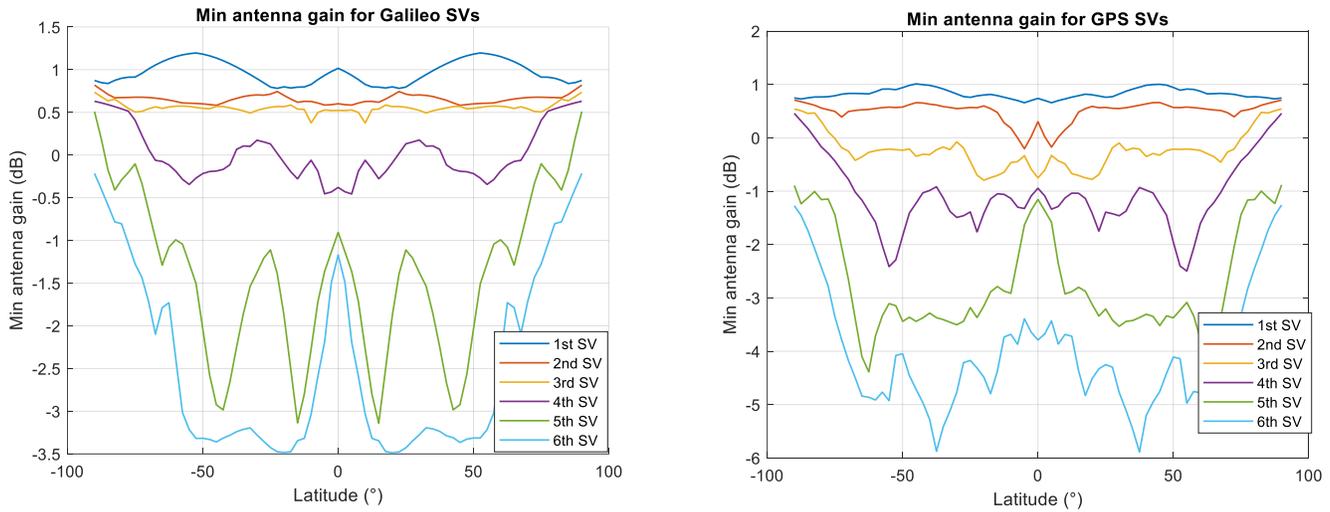
	GPS L1C/A	Galileo E1	GPS L5	Galileo E5a
$P_{GNSS}$ (dBW)	-158.5	-157.9	-154.9	-155.9

- $L_{imp}$  is the implementation losses. Implementation losses are defined in (C. J. Hegarty, 2011) as “decrease of signal to noise ratio due to bandlimiting, quantization and sampling”. Three parameters must be investigated to estimate an upper bound of implementation losses: quantization losses, correlation losses due to payload distortion and band-limiting and local replica mismatch losses. This analysis has been done in DO-235C for GPS L1C/A and Galileo DFMC receiver. For GPS L5 and Galileo E5a, the implementation losses have been calculated during the development of future released DO292A. Implementation losses for the different systems are summarized in TABLE 10 for DFMC receiver.

TABLE 10  
Implementation losses

	GPS L1C/A	Galileo E1	GPS L5	Galileo E5a
$L_{imp}$ (dB)	1.5	1.9	1.2	1.4

- $G_{ant}$  is the antenna gain of the GNSS receiver. For civil aviation DFMC GNSS receiver, the antenna is standardized according to DO-373 (RTCA, 2018), and the gain of a GNSS antenna equipped by an aircraft must have a pattern in-between a minimum and maximum pattern defined in DO-373. In this analysis, to consider a worst case scenario, the minimum DFMC antenna gain pattern is considered. According to TTF requirements presented in section 2.1, valid almanacs are supposed to be known when acquiring SVs. Therefore, it is proposed to acquire SVs in a decreasing elevation order, as SVs with the highest elevation are expected to have higher  $C/N_0$ . The elevation of the highest satellites depends on the GNSS configuration. To compute the minimum antenna gain at a given position and for a given constellation, the constellation is run over one orbit period. At each instant, the antenna gain of the highest elevation angle SVs are computed. The minimum antenna gain for the considered position (for each elevation angle satellite, for example 1<sup>st</sup>, 2<sup>nd</sup>, etc.) will be determined by taking first the minimum antenna gain value among all instants of the orbit period and second, by taking among all resulting longitude values for a given latitude the minimum antenna gain (to take into account the Earth orbit drift) As a result, a minimum antenna gain per satellite elevation angle order as a function of the latitude will be computed. The minimum antenna gain as a function of the latitude, for GPS and Galileo 24 SVs constellations, is shown in **Figure 11**.



**Figure 11** Minimum antenna gain

#### 4.1.2 Effective noise power spectral density

RFI sources impact on GNSS receiver is often modelled as an increase of the noise floor at the GNSS antenna port (although this modelling is not accurate for RFI with bandwidth smaller than the inverse of the correlation integration time). Indeed, signals using code division multiple access (CDMA) spread spectrum techniques are based on the spreading of a useful signal thanks to the multiplication with the pseudo random noise (PRN) code. In the receiver, the received signal is multiplied by a locally generated PRN code. The goal of this operation is to remove the PRN code on the useful signal in order to de-spread the useful signal. Other unwanted components of the received signal, such as RFI, are meanwhile spread by the multiplication with the locally generated

PRN code and are modelled as an AWGN. More details on the behavior of RFI on CDMA receivers can be found in (Johnson & Erlandson, 1995). The noise power spectral density in presence of RFI is called effective noise power spectral density  $N_{0,eff}$ . This definition also assumes that subsequent RFFE elements are considered as ideal (RF filter, IF filter, AGC/ADC), that the correlator is also considered ideal, and thus that these elements do not distort the GNSS useful signal.

The expression of effective noise depends on the presence or absence of a blanker in the receiver. A blanker is a RFI mitigation mechanism which removes/blanks part of the incoming signal that fulfills a certain condition; usually to exceed a blanker threshold. L5/E5a receiver must indeed use a blanker since, as it will be seen in the next section, nominal RFI environment include high power pulsed RFI. Expressions of effective noise is given in DO-292 (in presence of a blanker) and in DO-235 (without blanker). They are respectively recalled in Equations (28) and (29).

$$N_{0,eff} = \frac{N_0}{1 - PDC} \left( 1 + \sum_{X \in \text{Continuous RFI}} \frac{I_{0,X}}{N_0} + R_I + \frac{N_L^2 PDC}{1 - PDC} \right) \quad (28)$$

$$N_{0,eff} = \frac{N_0}{1 - BDC} \left( 1 + \sum_{X \in \text{Continuous RFI}} \frac{I_{0,X}}{N_0} + R_I \right) \quad (29)$$

- $N_0$  is the thermal noise.
- $PDC$  is the pulse duty cycle. It corresponds to the amount of time that the low noise amplifier (LNA) is saturated and does not operate in a linear way.
- $I_{0,X}$  is the equivalent noise of a continuous RFI  $X$ . The equivalent noise of an RFI source  $X$  is defined by the power spectral density  $I_{0,X}$  of a AWGN that would generate the same power at the correlator output as the RFI.
- $R_I$  is the ratio of below saturation (or below blanker) average pulse power density to  $N_0$ . It quantifies the effect of a pulsed RFI which is not powerful enough to reach the saturating point of the LNA (or to reach the blanker threshold).
- $N_L$  is the ratio of analog to digital saturation level to  $1 \cdot \sigma$  noise voltage established by AGC (equal to 1.5 for a 1.5 bit ADC).
- $BDC$  is the blanker duty cycle. It corresponds to the amount of time that the received signal power exceeds the blanker threshold and thus triggers the blanker.

## 4.2 Nominal RFI environment

This section describes the nominal RF environment for L1/E1 band and L5/E5 band. RFI sources can be split in two categories:

- **Aeronautical RFI:** Aeronautical sources gather all RFI transmitted from aeronautical systems. Therefore, they have an ITU (International Telecommunications Union) allocation to transmit in the GNSS band.
- **Non-aeronautical RFI:** Non-aeronautical RFI sources gather all RFI transmitted by non-aeronautical systems. Nominal RFI environment only considers involuntary spurious emission from non-aeronautical systems. Jamming is not included in nominal non-aeronautical RFI environment since it modifies the RFI environment on a time limited period and only on a limited area. Some acquisition requirements are also imposed to civil aviation DFMC receiver, but out of the scope of this article.

### 4.2.1 L1/E1 band nominal RFI environment

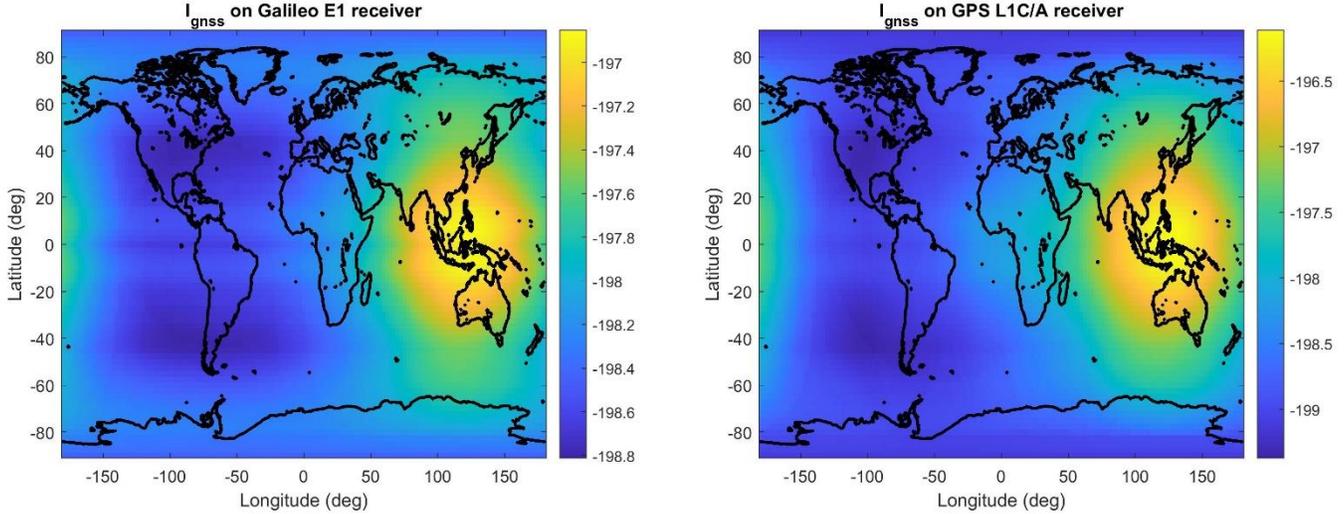
Nominal RFI environment in L1/E1 frequency band is described in DO-235C. Impact of L1/E1 RFI sources on efficient noise have been determined in DO-235C (reader is referred to this reference for more details).

Aeronautical RFI includes:

- 1) **AMSS:** Some aircrafts have an aeronautical mobile satellite system (AMSS) equipment. This on-board equipment allows communication between the crew and the ground through satellite communications. AMSS has a frequency allocation in the [1626-1660] MHz band and thus, AMSS transmission does not directly hit the GNSS L1 band. However, 5<sup>th</sup> and 7<sup>th</sup> order intermodulation terms fall into the L1 GNSS band and may degrade the GNSS signal processing. The total equivalent noise induced by AMSS is estimated to be  $I_{0,AMSS} = -215.98 \text{ dBW/MHz}$ .
- 2) **Case Emissions:** Cockpit devices screens also radiate unwanted energy in the GNSS L1 band. This aeronautical RFI source is referred as case emissions. Current cockpit installed equipment are tested and certified according to (Radio Technical Commission for Aeronautics, 2010) Cat M requirements. In particular, undesired radiation in the GNSS frequency band from each cockpit equipment device is limited to 53.3 dB $\mu$ V/m for this category of equipment, but some measurements that these devices do not transmit more than 40 dB $\mu$ V/m. Newer cockpit devices will be certified according to Cat P and Cat Q

requirements and will be allowed to transmit no more than 40 dB $\mu$ V/m. The equivalent noise induced by 12 cockpit devices has been quantified to be  $I_{0,case\ emission} = -208.98\text{ dBW/MHz}$  considering a radiated field on 40 dB $\mu$ V/m per device.

- 3) **Inter and intra system RFI:** Inter and intra system RFI refers to GNSS signals coming from other GNSS constellations or from the same constellation but from a different signal of interest. For example, Galileo E1 signals and GPS L1C/A PRN 6 signal act as an RFI on the receiver channel processing of GPS L1C/A PRN 2 signal. Inter and intra system RFI has been updated in DO-235C. Inter/intra system RFI equivalent noise on GPS L1C/A and Galileo E1 GNSS receivers is shown in **Figure 12**.



**Figure 12**  $I_{gnss}$  on Galileo E1 and GPS L1C/A receiver

Non-aeronautical sources of the nominal L1/E1 RFI environment include:

- On-board portable electronic devices (PEDs) carried by passengers,
- spurious emission induced by terrestrial emitters.

Equivalent noise of total non-aeronautical RFI sources has been estimated to  $I_{0,non\ aero} = -200.5\text{ dBW/MHz}$  when the receiver is located on the ground and including a 6dB safety margin.

Other parameters of Equation (28) are set as follows in DO-235C. It is supposed that the total power exceeds the saturation threshold less than 1% of the time, so  $PDC = 0.01$ . The L1/E1 frequency band is not affected by pulsed RFI in nominal situation, so  $R_l = 0$ . Eventually, for a 1.5 bit quantization receiver as used by DFMC receiver,  $N_l$  is equal to 1.5.

#### 4.2.2 L5/E5a band nominal RFI environment

Nominal RFI environment for the L5/E5a frequency band is defined in DO-292. Impact of Aeronautical RFI sources are still under revision as part of DO-292A MOPS elaboration. Instead of analyzing the RFI impact as a function of the receiver location as done during the revision A of DO-292, RFI sources are here only analyzed at a particular location (50.5°N;5.5°E) for which the link budget is expected to be the among the worst worldwide for ground operation. Nominal RFI environments in the L5/E5a sources include:

- Case emission:  $I_{0,case\ emission} = -206.43\text{ dBW/MHz}$
- Inter/intra system RFI at location (37.88°N;75.22°E):  $I_{0,gnss} = -202.37\text{ dBW/MHz}$
- Pulsed RFI caused by aeronautical system: Distance Measurement Equipment (DME), Tactical Air Navigation system (TCAN), Joint Tactical Information Distribution System (JTIDS) and Multifunctional Information Distribution System (MIDS).  $R_l$  and BDC at location (50.5°N;5.5°E) are estimated at  $R_l = 1.44$  and  $BDC = 0.24$ .
- Non-aeronautical RFI:  $I_{0,non\ aero} = -197.5\text{ dBW/MHz}$ .
- The thermal noise is  $N_0 = -200\text{ dBW/MHz}$

### 4.3 Link budget analysis

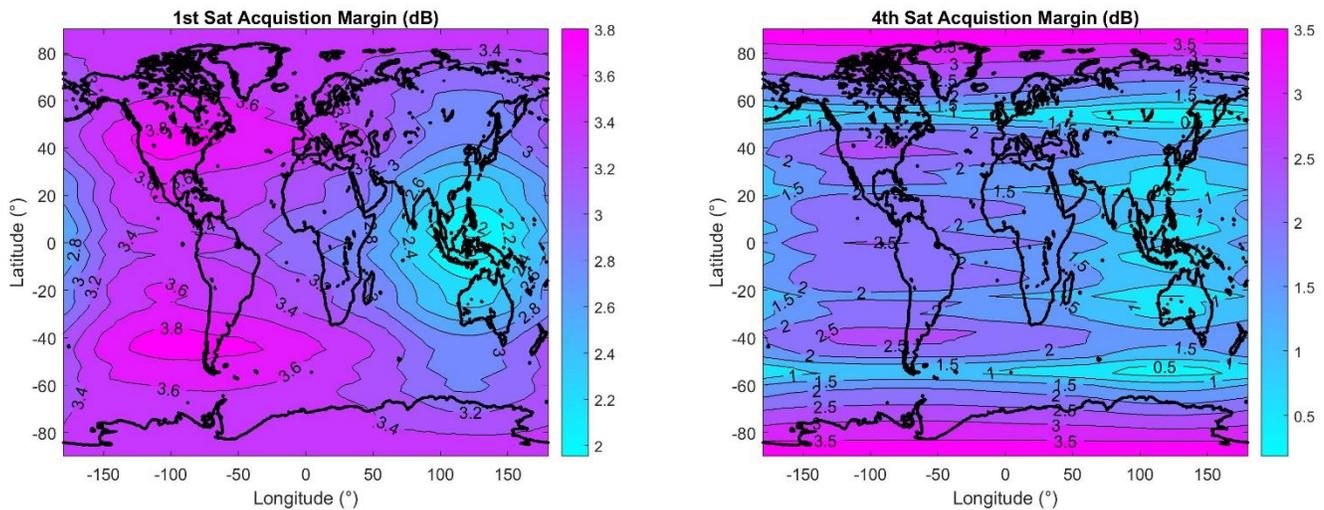
This section computes the  $C/N_0$  acquisition link budget margins for the different signals to be acquired. The link budget margin is defined in (30).

$$u_m = \frac{C/N_{0,eff}}{Th_{acq}} \quad (30)$$

The recovered signal power  $C$  is computed with (27), and effective noise is computed with (28) or (29) depending on the frequency band.

#### 4.3.1 L1/E1 link budget analysis

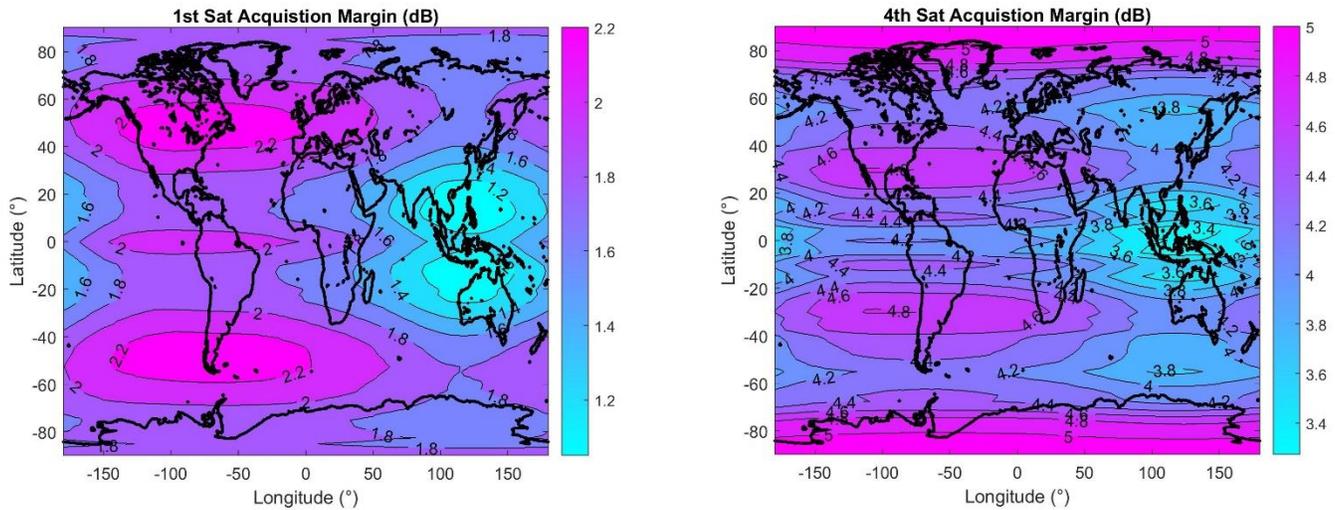
Section 4.1 defined the recovered GNSS signal power and section 4.2.1 provided the elements to compute the efficient noise power spectral density for DFMC receivers when processing GPS L1C/A, Galileo E1 signals. Therefore, it is now possible to compute the acquisition  $C/N_0$  link budget margin as a function of the location of the receiver. Indeed, two parameters of the link budgets vary with the position of the victim receiver. First, **Figure 11** shows a dependency of the highest satellites elevation and thus, of the receiver antenna gain, with the position of the victim receiver. Second, according to **Figure 12**, inter and intra system RFI also depends on the position of the victim receiver. **Figure 13** shows the acquisition  $C/N_0$  link budget margins for first and fourth GPS L1C/A SVs acquisition. It is computed comparing the  $C/N_{0,eff}$  computed from the recovered signal power of Equation (27) and the effective noise of Equation (28), with the acquisition threshold derived in section 3.



**Figure 13** Acquisition  $C/N_0$  link budget margin for GPS L1C/A signal

**Figure 13** shows positive  $C/N_0$  link budget margins. The margin is comfortable for the first satellite acquisition since the minimum margin across the world is around 2 dB. Because it is here supposed that SVs are acquired in a decreasing elevation order, second and third SVs have a link budget margin higher than the fourth SV link budget margin since the minimum antenna gain is higher (see **Figure 11**). The margin is lower for the fourth SV acquisition than for 1<sup>st</sup> SV acquisition since the minimum margin around the world is 0.18 dB. However, this margin, that has been computed from a worst situation for all the parameters of Equation (28), is still positive, meaning that the first fix can be performed with GPS L1C/A system within the allocated time and with the targeted probability of success anywhere around the world. In addition, the majority of current receivers allocate more correlators to the acquisition than the number considered here. To use more correlators during acquisition should make the acquisition  $C/N_0$  link budget margin increase. These positive link budget margins show the compliance of the presented strategy with DMS:306, as well as the compliance of the initial acquisition strategy with the obtention of a L1 navigation solution as part of DMS:199 requirement.

**Figure 14** shows the acquisition  $C/N_0$  link budget margins for first and fourth Galileo E1 SVs acquisition.



**Figure 14** Acquisition  $C/N_0$  link budget margin for Galileo E1 signal

**Figure 14** shows comfortable link budget margins for first and subsequent Galileo E1 SVs acquisition process. Therefore, Galileo E1 receiver should be able to compute a first fix within the allocated time (6.5 min) with the required probability of success. Since the link budget margins are positive, the presented initial acquisition strategy is therefore compliant with DMS:306, and also compliant with the obtention of E1 navigation solution as part of DMS:210 requirement.

#### 4.3.2 L5/E5a link budget analysis

Because acquisition  $C/N_0$  link budget parameters for GPS L5 and Galileo E5a are pending validation, and because they are not available worldwide but just at one position which is expected to have the smallest link budget margin for ground operations, the acquisition link budget for Galileo E5a and GPS L5 SVs acquisition are only computed at that point in this work. The acquisition  $C/N_0$  link budgets are given in TABLE 11.

TABLE 11 GPS L5 and Galileo E5a acquisition  $C/N_0$  link budget analysis

	GPS L5 1 <sup>st</sup> SV acq	GPS L5 4 <sup>th</sup> SV acq	Galileo E5a 1 <sup>st</sup> SV acq	Galileo E5a 4 <sup>th</sup> SV acq
Received power (dBW)	-154,9	-154,9	-155,9	-155,9
Antenna gain (dB)	0,9557	-0,9459	1,037	0,03785
Implementation losses (dB)	1,2	1,2	1,4	1,4
Recovered signal power (dBW)	-155,14	-157,04	-156,2	-157,26
Case emission RFI (dBW/Hz)	-206,43	-206,43	-206,43	-206,43
Inter/intra system RFI (dBW/Hz)	-203,57	-203,57	-203,57	-203,57
Non aeronautical RFI (dBW/Hz)	-197,5	-197,5	-197,5	-197,5
BDC	0,32	0,32	0,32	0,32
Ri	1,48	1,48	1,48	1,48
Effective noise (dBW/Hz)	-191,40	-191,40	-191,40	-191,40
$C/N_{0eff}$	36,26	34,35	35,14	34,14
Acquisition threshold	33	28,5	33	28,5
Link budget margin (dB)	<b>3,256435111</b>	<b>5,854835111</b>	<b>2,137735111</b>	<b>5,638585111</b>

The link budget margins computed in TABLE 11 are very comfortable. That confirms the feasibility of ground acquisition in nominal RFI environment conditions. However, RFI environment at high altitude is expected to be more constraining, because of a higher number of ground DME and TACAN beacons in view from a RF perspective. But at high altitude, acquisition threshold for the 1<sup>st</sup> SV is supposed to be higher thanks to a lower uncertainty on receiver clock derivation (at high altitude, the receiver indeed performs a warm start acquisition instead of a cold start acquisition at low altitude) and thus, the number of bins in the acquisition matrix is expected to be lower. Even though the acquisition threshold is not modified for 4th SV acquisition, the margin is very comfortable, and the link budget is still positive at high altitude as well. These positive link budget margins demonstrate the capacity of GNSS receiver to compute a L5/E5a navigation position with the assumed initial acquisition strategy compliant with DMS:199 and DMS:210 TTFF requirements.

As a conclusion, all the acquisition  $C/N_0$  link budget margins are positive. Therefore, DFMC TTFF requirements can be fulfilled using the acquisition strategy presented in this article.

## 5 CONCLUSION

The objective of this article is to derive acquisition thresholds compliant with new ED-259 DFMC TTFF requirements. DFMC TTFF requirements are first presented and analyzed. The innovation is the 15 min DFMC initial acquisition with SBAS L5 augmentation. From this analysis, an DFMC acquisition strategy is proposed in accordance with DFMC TTFF requirements. This strategy is not optimal in terms of acquisition performance. However, it has the advantage of being simple and guarantees the ability to perform a standalone acquisition for each system in a limited duration. Second, a mathematical derivation of acquisition thresholds is performed. Acquisition thresholds strongly depends on the size of the acquisition matrix as well as the number of correlators dedicated to acquisition. The retained acquisition thresholds values in standards are:

- For GPS L1C/A: 32.4 dB-Hz for the 1<sup>st</sup> SV acquisition (20 correlators), 31.7 dB-Hz for subsequent SVs (10 correlators). Historically, these acquisition thresholds have been computed considering a low number of correlators. However, DFMC receiver should have a higher capacity in terms of number of correlators, so these acquisition thresholds may be decreased by allocating more correlators to the acquisition process.
- For Galileo E1: 34.1 dB-Hz for 1<sup>st</sup> SV acquisition (400 correlators), 30.6 dB-Hz for the acquisition of subsequent SVs (400 correlators).
- For Galileo E5a and GPS L5: 33 dB-Hz for 1<sup>st</sup> SV acquisition (200 correlators), 28.5 dB-Hz for subsequent SV acquisition (200 correlators).

Note that the acquisition threshold values provided here are for cold start acquisition. The acquisition threshold of the 1<sup>st</sup> SV would be reduced when considering a warm start acquisition.

Third and last, this article analyzed the capacity of the receiver to meet DFMC requirements under nominal RFI environment, computing acquisition  $C/N_0$  link budgets. Link budget margins are positive. The minimum link budget margin is obtained for the acquisition of the 4<sup>th</sup> GPS L1C/A signal, and the link budget margin is 0.2 dB. Margins for acquisition of other signal are more comfortable: at least 1 dB for Galileo E1 acquisition, and at least 2.1 dB for Galileo E5 and GPS L5 signals acquisition. As the link budget margins are all positive, the proposed simple strategy is sufficient to fulfill DFMC TTFF requirements under nominal RFI environment.

To complete this theoretical assessment, acquisition TTFF performance, demonstrated here through a theoretical approach, may be completed by receiver testing with Monte Carlo simulations.

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