In-band RFI GNSS L5/E5a Mask Definition

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BIOGRAPHIES

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Mikael MABILLEAU is a standardisation engineer on SBAS in the EGNOS exploitation team of the European GNSS Agency (GSA). Since his graduation as engineer from the French civil aviation school (ENAC) in 2006, he has been involved in GNSS standardization activity carried by the main civil aviation standardisation bodies such as the EUROCAE WG 62 on Galileo, RTCA Special Committee 159 on GPS and the International Civil Aviation Organisation (ICAO) Navigation System Panel in charge of ICAO standard. Mikael is involved in the evolution of GNSS concepts (ARAIM and SBAS L1L5) supporting the development of the associated standards (SARPs and MOPS) for use in aviation.

Pierre DUREL graduated in 2002 from the University of Montpellier II as an engineer specialized in hyper-frequencies and optronics. He is working as EGNOS Services Engineer for the European GNSS Agency. He is involved in standardization activities dealing with DFMC SBAS for which he is secretary of EUROCAE Galileo Working Group 62.

ABSTRACT

A long series of scientific publications have presented to revisit several aspects of the Radio Frequency Interference (RFI) impact on the airborne L5/E5a band GNSS receiver. The main objective was to define, for the first time, L5/E5a GNSS RFI masks. This long series of publications are culminated with this work where the concept of RFI GNSS mask is reminded and the methodology used to derive these masks is provided. This methodology will be used to derive L5/E5a GNSS RFI masks or interference thresholds to be published in different aviation standards such as ICAO SARPS and RTCA/EUROCAE MOPS (RTCA DO-292 update).

The presented methodology will be mainly focused on the L5/E5a GNSS RFI mask and will make reference to other scientific words which are used to characterize necessary inputs to derive the mask, such as the contribution of the different aeronautical interfering sources. In this work, the physical link between the RFI mask interpretation

and mathematical model of a RFI impact on a GNSS receiver will be made and the maximum impact allowed to a non-aeronautical RFI source, in terms of power, bandwidth and central frequency, will be explained. The concept of link margin will be introduced as well as the elements determining its value. From the concept of link margin and RFI impact, the L5/E5a GNSS RFI mask derivation methodology will be explained as well as the necessity to inspect the link margin for any signal / basic signal processing function pair.

INTRODUCTION

Global Navigation Satellite System (GNSS) received signals processing can be affected by received additive signals such as noise, multipath and interference. Radio Frequency Interference (RFI) sources are of various sorts and their nature and impact depends on the user application. In the context of civil aviation, it is important to identify and to characterize the radio frequency interference relevant to the airborne GNSS receivers processing signals in the L1/E1 and L5/E5a bands: to determine the vulnerability of airborne GNSS receivers in L1/E1 and L5/E5a equipped with their relevant antenna, to issue minimum requirements on these L1/E1 and L5/E5a antennas, to issue minimum requirements to be imposed to airborne GNSS receivers operating at L1/E1 and L5/E5a bands as well as to define RFI compatibility masks with non-aeronautical systems.

The RFI impact on a GNSS receiver in civil aviation is usually modelled as the overall carrier to receiver thermal noise density C/N_0 degradation observed at the receiver's correlator output, or equivalently, as an increase of the effective receiver noise density N_0 with added interference denoted as $N_{0,eff}$. Therefore, a decrease of the minimum available C/N_0, derived from the link budget and from the $N_{0,eff}$ calculation, implies a reduction of the C/N_0 margin between the minimum available $C/N_{0,eff}$ and the different L5/E5a GNSS and SBAS signal processing, acquisition, tracking, demodulation, C/N_0 threshold values. From this link margin and from translating its influence on RFI signal power which reduces this margin to zero (airborne GNSS receivers nominal performance are no longer guaranteed), RFI compatibility masks and RFI tests can be defined and can be included in different standards. Note that the RFI GNSS L5/E5a masks define the maximum power authorized to a non-aeronautical interfering signal (since all aeronautical interfering signals impact is already accounted for) as a function of its bandwidth and its carrier frequency.

A long thread of RFI analysis activities led to the elaboration of various ICAO, RTCA and EUROCAE standards considering RFI. Currently, RTCA DO-292 [1] reflecting the relevant interference to L5/E5a is being updated to incorporate the evolutions of the RFI environment defined by DME/TACAN, JTIDS/MIDS, SSR equipment and other GNSS systems operating at these bands, as well as the usage of this L5/E5a band for GALILEO E5a and SBAS L5/E5a datalink airborne signal processing. Moreover, ICAO RFI mask of GNSS L5/E5a is now under definition for the first time. These elements will then complement the current ICAO SARPs, draft EUROCAE and RTCA MOPS for GNSS L5/E5a airborne receivers.

In the course of the elaboration of the update of [1] and for the ICAO GNSS L5/E5a RFI mask definition, several elements of the worst-case scenario link budget analysis have been revisited in order to consolidate the overall link budget margin. This was deemed necessary since the link budget margin is expected to be very small. Among the axes of revision were:

- the analytical model representing the effect of the temporal blanker: the model for blanking function has gone under new scrutiny, with the prospect of the definition of a minimum blanker model [2].
- the DME/TACAN environment and its impact on minimum operational/system performance requirements for a GNSS L5/E5a receiver: the DME/TACAN environment has been reviewed and new interfering parameters have been calculated [4].
- the JTIDS/MIDS environment and its impact on minimum operational/system performance requirements for a GNSS L5/E5a receiver: models of impact of DME/TACAN on C/N_0 degradation have also been revised and new formulas have been derived [3]; moreover, the JTIDS/MIDS environment have been re-assessed, and the relevant models updated in [5].
- Re-evaluation of the intra and inter-system RFI impact: a review of the GNSS intra-system environment has been conducted in [6] in order to take into account the new minimum and maximum powers of the GNSS, regional and augmentations systems transmitting in the L5/E5a band; this review also considered the inclusion of new signal components such as GEO SBAS L5 and the prevision of potential IGSO SBAS satellites transmitting at L5.

From the update of all these axes of revision presented in a series of scientific publications, the new C/N_0 margin between the minimum available $C/N_{0,eff}$ and the different L5/E5a GNSS and SBAS signal processing, acquisition, tracking, demodulation, C/N_0 threshold values can be calculated. And from this margin the RFI GNSS L5/E5a masks can be derived. This paper aims thus to present the methodology which should be used to derive RFI GNSS masks and to apply the presented methodology to derive the RFI GNSS L5/E5a mask.

The paper is organized as follows. First, the general definition of a RFI mask as well as the specific definitions of in-band/near-band and out-of-band RFI mask are provided. Second, the impact of a RFI in a GNSS receiver is mathematically described and the link of its physical characteristics, power, signal bandwidth and central frequency, are physically related to the RFI mask derivation. Third, a methodology to derive the RFI masks is proposed, justified and detailed. Fourth, the proposed methodology is used to derive the L5/E5a GNSS in-band/near-band and out-of-band RFI masks. Finally, the analysis is concluded.

1) IN-BAND/NEAR-BAND AND OUT-OF-BAND RFI MASK DEFINITIONS

In this section, first a general definition of an aeronautical RFI mask is given and second, the specific definitions, and published examples, are given for the two specific types of RFI mask being defined in the standards.

1.A) General aeronautical RFI mask definition

An aeronautical RFI mask can be defined as the total amount of power which can be tolerated by an aeronautical GNSS receiver, at its antenna port, from the aggregated of non-aeronautical signal sources, with a given signal bandwidth BW and with a given central frequency f_c, without affecting the aeronautical GNSS receiver nominal performances when the receiver is already inherently affected by aeronautical interference.

There are several key terms in the previous definition:

- The term “tolerate” implies that the non-aeronautical sources aggregate does not degrade the nominal Safety of Life (SoL) performance of any aeronautical GNSS/SBAS receiver basic signal processing function: acquisition, tracking and demodulation.
- The GNSS receiver antenna port is defined at the antenna’s passive element output.
- Total power of the aggregate of non-aeronautical RFI signal sources must be tolerated in addition to the aeronautical RFI sources which will also impact the receiver. Other aeronautical RF sources, which are seen as RFI from the perspective of the processing of a given GNSS signal, will always be present since they have the same priority to be transmitted as the targeted GNSS signal (e.g. other GNSS signals) or even have a higher priority (band allocation) as is the case for DME/TACAN systems.

Finally, depending on the interference signal bandwidth, BW, and on the interfering central frequency, f_c, with respect to the GNSS/SBAS central frequency, f_{L1orL5}, defined as the frequency interference offset, Δ_f, two types of RFI masks are defined:

1) In-band/Near-band RFI mask
2) Out-of-band RFI mask

<u>Important remark:</u> note that the RFI mask represent the maximum source tolerable power which the non-aeronautical source aggregate is allowed to have (at the airborne GNSS receiver antenna port). This means that the information provided by the RFI mask must be used with care. In the case of defining receiver tests, the interpretation is quite straightforward since usually only one non-aeronautical signal source is defined. However, when using the RFI masks for compatibility purposes, due to the fact that more than one non-aeronautical source is present, RFI masks should be analyzed carefully:

- If all non-aeronautical sources have the same bandwidth and carrier frequency, the total tolerable power must be divided among the different sources: each individual source is not allowed to have the power indicated by the mask; the allowed power must be shared.
- If the non-aeronautical sources have different bandwidth and/or carrier frequencies, how much power is allocated to each source must be analyzed carefully from the information provided by the RFI masks, so that the total contribution of the sources aggregated does not degrade the airborne GNSS receiver nominal performance.

1.B) In-band/Near-band RFI mask

In-band/Near-band RFI mask is defined as the RFI mask for a variable band-limited, BW_i, noise-like non-aeronautical RFI source with frequency offset range, Δ_{f_i}, equal to half the useful GNSS signal bandwidth or half the RFI signal bandwidth; depending of which of the two is larger. Therefore, the interference frequency carrier range, f_{c_i} is equal to:

$$f_{c_i} = f_{L1orL5} \pm \max(BW_{GNSS-SBAS}/2, BW_i/2) \quad (1)$$

An example of in-band/near-band RFI mask is given in Figure 1. Figure 1 presents the GPS L1 and SBAS L1 in-band/near-band interference mask, also called interference thresholds, published in the ICAO SARPS Volume 10 appendix B [9]. From this figure, it can be seen the maximum tolerable power, expressed in dBW, which can be tolerated by a GPS or SBAS L1 receivers without degrading nominal receiver performance. The interference bandwidth, BW_i, varies between 10Hz and 100MHz and it can be observed that maximum tolerable power increases along the interference bandwidth increase. This is due to the RF/IF/antenna filters as well as the GNSS receiver correlation process (as will be seen in section 2.C). In this case, the analyzed interference carrier frequency is equal to 1575.42MHz + $BW_i/2$.

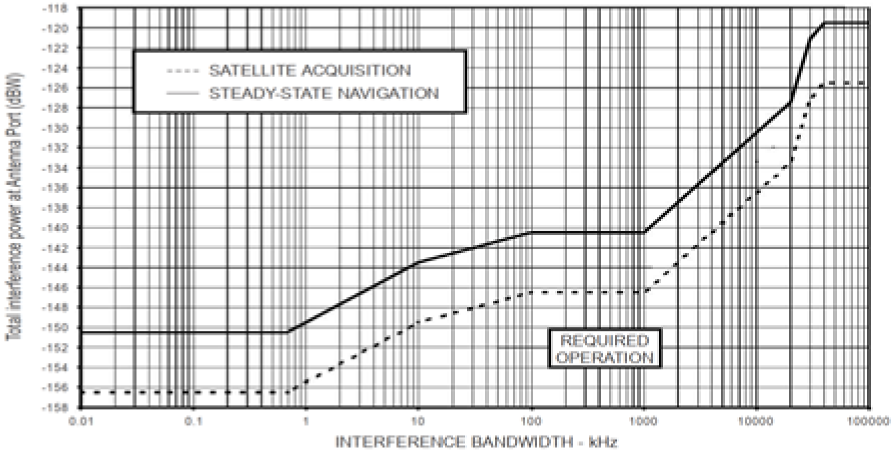

Figure 1: Interference thresholds versus bandwidth for GPS and SBAS receivers [9]

1.C) Out-of-band RFI mask

The Out-of-band RFI mask is defined as the RFI mask for a band-limited noise-like non-aeronautical interference source with a fixed BW_i which can be present in a very large carrier offset frequency range ($\Delta_f \gg$). Usually, the fixed bandwidth is relatively small, 1kHz, and the Out-of-band RFI mask can also be interpreted as the receiver robustness against CW-like interferences. Moreover, the analyzed frequency offset range is much larger than the one for the In-band/Near-band RFI mask: $\Delta_{f,In-band/Near-band} \ll \Delta_{f,Out-of-band}$.

An example of Out-of-band RFI mask is given in Figure 2. Figure 2 presents the GPS L1 and SBAS L1 out-of-band interference mask, also called interference thresholds, published in the ICAO SARPS Volume 10 appendix B [9]. From this figure, it can be seen that the maximum tolerable power depends on the interference carrier frequency offset, Δ_{f_i}. It can also be seen that more power is tolerable for interference carrier frequencies further apart from the L1 central frequency due to the equivalent RF/IF/Antenna filter of the GNSS receiver, and due to the Spectral Separation Coefficient (SSC) between the interference signal and the GNSS receiver PRN local replica which decreases along a larger separation between the interference and L1 central frequencies (as will be seen in section 2.C).

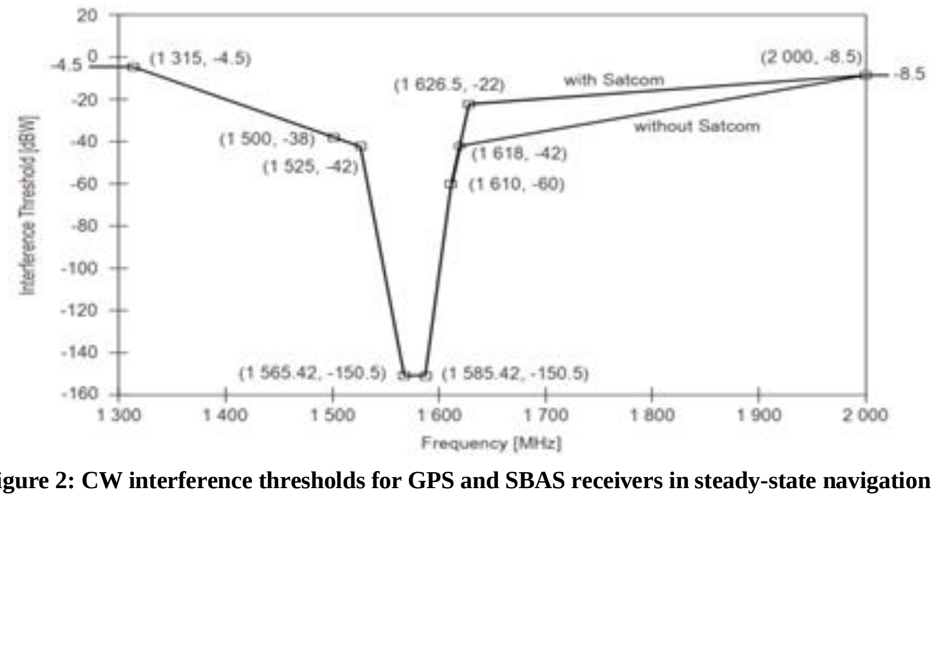

Figure 2: CW interference thresholds for GPS and SBAS receivers in steady-state navigation [9]

2) UNDERSTANDING OF C/N_0 DEGRADATION ANALYTICAL MODEL AND RFI IMPACT MODEL

In order to determine the RFI mask, it is important to translate the RFI definition given in the previous section into physical and mathematical concepts. The two keys points of this translation are first to mathematically model the impact of a RFI on an aeronautical GNSS receiver, which in the civil aviation field is a degradation of the observed C/N_0, and second to link the degraded C/N_0 with the concept of guaranteeing GNSS receiver nominal performance. The objective of this section is to provide and to explain this physical and mathematical link.

2.A) Generic airborne civil aviation GNSS receiver

In order to understand the C/N_0 degradation analytical model and in order to understand the RFI impact mathematical model, a generic airborne civil aviation GNSS receiver structure as well as the behavior and effect of its components on the received signals are described. This explanation is especially important due to the specific structure of an airborne L5/E5a GNSS receiver which implements a blanking mechanism to mitigate highly present aeronautical pulse interferences (DME/TACAN, JTIDS/MIDS, SSR, etc). In fact, the blanking mechanism has a direct influence on RFI impact on the GNSS receiver and on the C/N_0 degradation.

In Figure 3, a generic airborne L5/E5a GNSS receiver structure is presented.

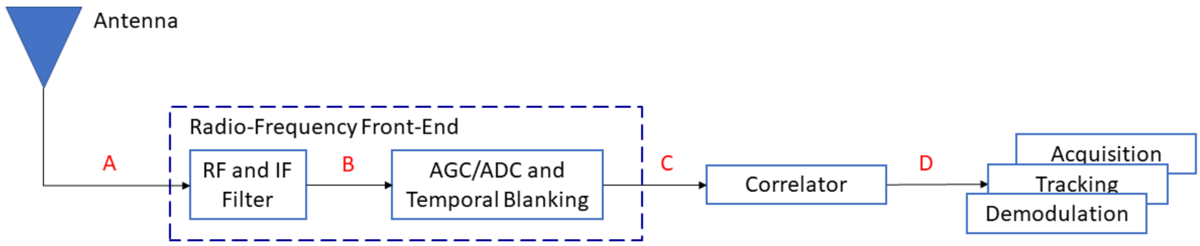

Figure 3: Generic civil aviation GNSS receiver block scheme

First, the antenna is the element responsible of capturing the incoming signal: at the antenna port (point A), there is a mix of all incoming signals; useful signals, GNSS and SBAS signals, and RFI signals such as DME/TACAN, JTIDS/MIDS, etc. Once the signals have been captured by the antenna, they are passed to the Radio-Frequency Front-End (RFFE) block. This block amplifies the received signals, shifts them from their received signal frequency carrier to the intermediate frequency and filters them (removing the image frequency, removing the spurious frequencies and removing the signal outside the interest frequency bandwidth). The filtered signals are modelled in Figure 3 at the RF (Radio-Frequency) and IF (Intermediate Frequency) filters output at point B. RTCA DO-292 [1] defines the joint effect of these two filters plus the antenna filtering effect with an equivalent filter transfer function; the equivalent transfer function, $H_{RF}(f)$, for a 20MHz filter bandwidth is provided in Figure 4.

The RFFE block is also responsible for gain control and digitizing the filtered signals with the application first of the AGC (Automatic Gain Control) circuit followed by ADC (Analog-Digital-Converter). In the proposed airborne civil aviation L5/E5a GNSS receiver, the digital pulse blanker is introduced after the RFFE block. As explained in the introduction, the blanker is a device which is going to blank (put to 0s) the time and/or frequency samples of the incoming signal (mix of signals) which exceed a set threshold; the digitized and blanked signal is found at point C. In RTCA DO-292 [1], the defined blanker is a temporal blanker called ***instantaneous blanker***.

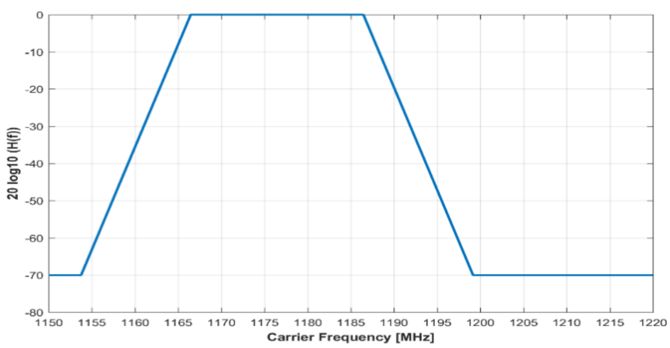

Figure 4: RFFE plus antenna equivalent transfer function defined in DO292 customized for a BW=20MHz

This blanking mechanism removes all the incoming signal time samples which have a power over a given threshold (issues concerning its actual description and physical implementation are addressed in **Erreur ! Source du renvoi**

introuvable.), see Figure 5. For an optimal functioning, the blanker should also be coupled with the ADC/AGC blocks: to ensure that high-power pulses are not saturating the ADC/AGC and the blanked signal spans the ADC quantization range. The effect of the AGC/ADC and its coupling with the blanker are out of scope of this paper. Finally, digitized and blanked signals are fed to the correlator and it is at its output (point D) where the impact of the RFI signals and the blanking method is measured. Finally, the RFI signals at the correlator output (point D of Figure 3) is where the demodulation, acquisition and tracking capabilities of the receiver can be impacted. It is at this point that these impacts are predicted and simulated within the analysis in this paper.

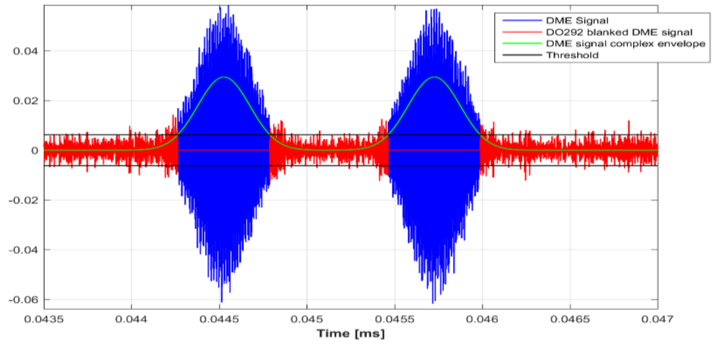

Figure 5: Example of the behavior of the DO-292 instantaneous blanker over the signal complex envelope

2.B) Effective C/N_0, C/N_0 degradation and general analytical model

The key figure of merit to analyze the RFI signals impact and the blanking method impact is the signal C/N_0; or more specifically, the difference between the C/N_0 when only the useful signal is present at the receiver antenna port (no RFI signals) and the C/N_0 when the useful signal and RFI signals are present at the receiver antenna port (with blanker activation), also called effective C/N_0 or $(C/N_0)_{eff}$. The difference between these two C/N_0 values is also called the C/N_0 degradation introduced by the RFI signals and the blanking method.

Although the blanking method is going to reduce the average power of the useful signal (part of the information signal is removed as well as part of the noise), RTCA DO-292 [1] proposes to model the $(C/N_0)_{eff}$ by defining an equivalent $N_{0,eff}$ while keeping the original useful power C. Note that $N_{0,eff}$ represents the effective noise power spectrum density that a receiver will observe at the correlator output if the receiver captures a useful signal with power C at the correlator output. This assumes that subsequent RFFE elements are considered as ideal (RF filter, IF filter, AGC/ADC), the correlator is also considered ideal, there are no RFI signals present and the blanker is not activated. In other words, in section 2.6.2.3, RTCA DO-292 [1] recommended a generic formula to compute the degradation of the C/N_0 through the increase of the background noise due to pulsed and continuous RFI, based on rigorous evaluation within the RTCA Special Committee 159. Note that from this definition, the $(C/N_0)_{eff}$ and C/N_0 when only the useful signal is present values, and the difference between the two, are expressed *at point A* of Figure 3 while they are calculated *at point D* (correlator output) when considering the impact of all the elements between the two points.

A detailed explanation on how $(C/N_0)_{eff}$ is derived and which are the assumptions made to obtain this derivation is given in [3]. The $(C/N_0)_{eff}$ can be directly derived from C (which absorbs the implementation losses term) and $N_{0_{eff}}$. The $N_{0_{eff}}$ expression, given by RTCA DO-292 [1] and detailed in [3], is reminded below:

$$N_{0,eff} = \frac{N_0}{1 - bdc} \cdot \left(1 + \frac{I_{0,WB}}{N_0} + R_I\right) \quad (2)$$

Where :

- N_0 is the thermal noise power spectrum density level generated by the RFFE
- bdc is the blanking duty cycle
- $I_{0,WB}$ is the power spectral density of aggregated continuous broadband RFI
- R_I is the total below-blanker pulse interfering-signal-to-thermal-noise ratio

Developing the previous terms, it can be seen

$$R_I = \sum_{i=1}^{I} R_{I,i} \quad (3)$$

$$I_{0,WB} = I_{0,\text{aero},WB} + I_{0,\text{non\_aero},WB} \quad (4)$$

Where:

- $R_{I,i}$ is the i^{th} source below-blanker interfering-signal-to-thermal-noise ratio
- $I_{0,\text{aero},WB}$ is the power spectral density of aggregated aeronautical continuous broadband RFI
- $I_{0,\text{non\_aero},WB}$ is the power spectral density of aggregated non-aeronautical continuous broadband RFI

Therefore, $I_{0,\text{non\_aero},WB}$ is the term used to model the degradation of C/N_0 (decrease of effective C/N_0) due to the presence of continuous non-aeronautical interference. This term must thus be related to the PSD, bandwidth, carrier frequency and power of a RFI in order to define the RFI mask as previously explained. This relationship is established in section 2.C).

For the sake of completeness, the expression of $R_{I,i}$ can be found in [3] where the expression proposed by RTCA DO-292 [1] and new one more accurate are given. Concerning $I_{0,\text{aero},WB}$, it can be further decomposed in three terms (at the epoch of the articles publication):

$$I_{0,\text{aero},WB} = I_{GNSS} + I_{0,cem} + I_{0,SATCOM} \quad (5)$$

Where:

- I_{GNSS} is the equivalent noise PSD of interference of other GNSS satellite transmitting within the same band (intra- and inter-system interference). This term is analyzed in [6]
- $I_{0,cem}$ is the equivalent noise PSD of avionics radiated interferences
- $I_{0,SATCOM}$ is the equivalent on-board aeronautical mobile satcom (AMSS)

2.C) RFI impact mathematical model:

The impact of a continuous RFI on a GNSS receiver can be mathematically modelled as an increase of the effective N_0 (or equivalently as a decrease of the effective C/N_0). The increase of the effective N_0 is made through the addition of an equivalent noise PSD generated by the continuous RFI, $I_{0,int}$. It is fundamental to obtain the relationships between this term, $I_{0,int}$, and the power, PSD, bandwidth and carrier frequency of the interference in order to derive the RFI mask.

The establishment of this relationship has already been made in [3] for pulse and for continuous interference with/without the presence of the blanking mechanism. In this section, just a quick reminder is provided for continuous interference. The reader is invited to consult [3] for further details.

This model is derived from the analysis of the impact of AWG noise at the correlator output. A generic scheme of a correlator is given in Figure 6. In this figure, the effect of the reception of a RFI in the C/N_0 is also illustrated.

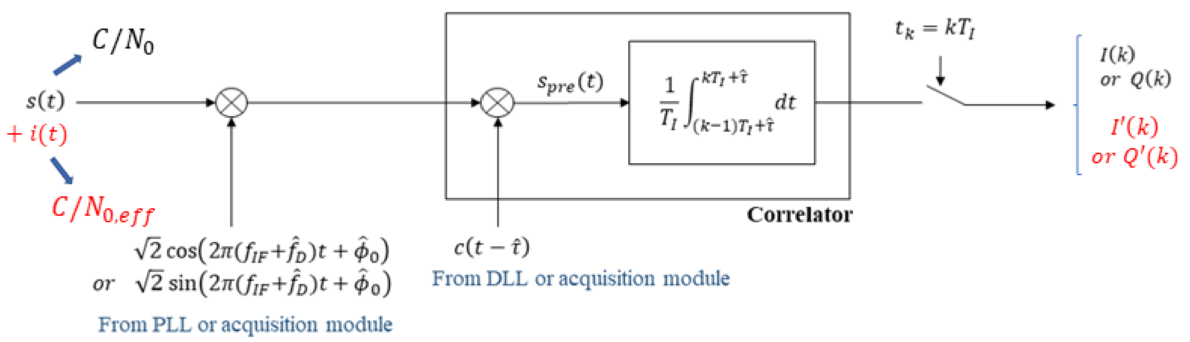

Figure 6: Generic civil aviation GNSS receiver block scheme

From [3] and taking into account that the blanking duty cycle, bdc, experienced by a continuous signal is equal to the total blanking duty experienced by the useful signal or the thermal noise, the mathematical model of $I_{0,int}$ is equal to:

$$I_{0,int} = \frac{1}{\beta_0} C_{int} \cdot SSC_{int} \tag{6}$$

$$\beta_0 = \int_{-\infty}^{+\infty} \left| H_{RF,BB}(f) \right|^2 \bar{S}_{c_m}(f) df \tag{7}$$

$$SSC_{int} = \int_{-\infty}^{+\infty} \left| H_{RF,BB}(f) \right|^2 \cdot \bar{S}_{interf,BB}(f - \Delta f) \cdot \bar{S}_{cm,L}(f) \cdot df \tag{8}$$

Where:

- C_{int} is the interference power
- β_0 is the reduction of AWGN power due to the antenna + RF/IF filters
- SSC_{int} is the spectral separation coefficient between the GNSS receiver local replica and the analysed RFI signal
- $\bar{S}_{c_m}$ is the normalized PSD of the local replica of the m^{th} PRN code used by the correlator
- $H_{RF}(f)$ is the baseband transfer function of the equivalent RFFE plus antenna filter
- $\bar{S}_{interf,BB}(f)$ is the normalized baseband PSD of the RFI signal

Moreover, the PSD of the considered RFI for RFI masks derivation purposes is always assumed to be a rectangular PSD; which is thus completely defined by its bandwidth. Therefore, the previous expressions can be rewritten as:

$$I_{0,int} = \frac{1}{\beta_0} C_{int} \cdot SSC_{rec}(BW, \Delta_{\mathrm{f}}) \tag{9}$$

$$SSC_{rec}(BW, \Delta_{\mathrm{f}}) = \frac{1}{BW} \int_{-BW/2+\Delta_f}^{+BW/2+\Delta_f} \left| H_{RF,BB}(f) \right|^2 \cdot \bar{S}_{cm,L}(f) \cdot df \tag{10}$$

Therefore, equations (9) and (10) show the relationship between a square PSD RFI signal with power C_{int}, BW and Δ_f and the increase of the AWG noise floor (weighted by the $1 - bdc$ term) that the RFI signal creates. This relationship is mainly due through the application of the Spectral Separation Coefficient (SSC). From these expressions, it can be seen that due to the RFFE equivalent filter shape (see Figure 4), RFI signal with carrier frequencies far from the GNSS signal carrier frequency ($\Delta_f \gg$) will impact less the receiver than frequencies falling inside the useful GNSS signal band ($\Delta_f \leq BW_{GNSS}/2$). Moreover, from these expressions, it can be seen that a RFI signal with a large bandwidth ($BW \gg$) will impact less the GNSS receiver than a RFI signal with a narrow bandwidth because the impact over $\bar{S}_{cm,L}$ will be averaged (averaging of the PSD rays), whereas for the narrow bandwidth RFI signal, a worst case can be found if the signal falls over the highest PSD rays.

One important remark must be done about equations (6) and (8). These equations assume that the RFI signal PSD is not modified by the blanking mechanism which is not true. Nevertheless, it can be shown that keeping the PSD before-blanker provides worst SSC results than using the post-blanker PSD (as could be inferred in [3] from the analysis of R_I proposed formulas). In fact, the effect of the blanker mechanism is to whiten the PSD of the incoming signals (to spread the PSD), and, as has been shown in Figure 1 (in-band/near-band L1 RFI mask), signals with larger bandwidth have a lower impact than signals with narrower bandwidth. Therefore, equations (9) and (10) can be interpreted as a worst-case scenario or as an upper bound of the RFI signal impact.

2.D) Link Margin, $u_{marg-link}$, and $I_{0,non-aero,mask}$ physical interpretation

Once the relationship between the C/N_0 degradation (or effective C/N_0) and the interference power, bandwidth and carrier frequency has been established, it only remains to link the effective C/N_0, $C/N_{0,eff}$ (in the presence of non-aeronautical interference) and the physical definition of the RFI mask, "maximum tolerable power which does not degrade the nominal airborne GNSS receiver performance", to complete the relationship between the interference power, bandwidth and carrier frequency, and the RFI mask mathematical derivation.

In order to achieve this objective, the link margin, $u_{marg-link}$, definition must be introduced first. The link margin of a given signal for a given basic signal processing function (acquisition, tacking, demodulation) is defined as the difference between the link budget C/N_0 of the given signal, also defined as $C/N_{0,eff}$, and the basic function C/N_0 threshold, $C/N_{0,th}$.

$$u_{marg-link} = C/N_{0,eff} - C/N_{0,th} \tag{11}$$

Therefore, knowing that:

- By RFI mask definition, the maximum tolerable power of the non-aeronautical RFI source aggregate must not degrade nominal aeronautical GNSS/SBAS receiver performance
- $C/N_{0,eff}$ is degraded (decreased) by the presence of non-aeronautical interference sources
- In order to guarantee nominal airborne GNSS receiver performance, the $C/N_{0,eff}$ of a given signal must be equal to or higher than the different basic signal processing functions thresholds associated to the signal, $C/N_{0,th}$, or in other words, the link margin, $u_{marg-link}$, must be positive.

It can be stated that:

- In the presence of non-aeronautical interference, the maximum RFI signal power which can be tolerated for a given bandwidth, BW, and carrier frequency, f_c, is the power which makes the link margin, $u_{marg-link}$, equal to 0.

Therefore, $I_{0,non-aero}$ determining RFI mask, $I_{0,non-aero,mask}$, can be interpreted as the maximum value of $I_{0,non-aero}$ which induces a $N_{0,eff}$ increase such that the link margin is equal to 0. This statement can also be interpreted as the increase of $N_{0,eff}$, due to the presence of non-aeronautical RFI, being equal to the link margin (link margin calculated when no non-aeronautical RFI is present). The mathematical relationship is given below:

$$u_{marg-link} = \underbrace{\frac{1}{(1-bdc)}\left(N_0 + \frac{I_{0,aero,wb}}{N_0} + \frac{I_{0,non-aero}}{N_0} + R_I\right)}_{N_{0,eff}\ with\ non-aero\ RFI\ source\ aggregate} - \underbrace{\frac{1}{(1-bdc)}\left(N_0 + \frac{I_{0,aero,wb}}{N_0} + R_I\right)}_{N_{0,eff}\ without\ non-aero\ RFI\ source\ aggregate} \tag{12}$$

Equations (9) to (12) are the basis for the RFI mask derivation; or in other words, they are the basis to derive C_{max}, the maximum tolerable power, as a function of the RFI signal bandwidth and carrier frequency.

3) RFI MASK DERIVATION METHODOLOGY

In this section, the detailed methodology to derive GNSS RFI mask as well as the fundamental idea behind the methodology are explained.

3.A) Factors determining the RFI Mask and GNSS RFI mask derivation methodology fundamental idea

One important concept about the GNSS RFI mask is that the RFI mask should cover the worst-case in terms of maximum tolerable power. This means that the driving scenario for the RFI mask derivation must be the scenario where the lowest maximum tolerable power, C_{max}, is found. Therefore, all potential scenarios must be inspected in order to determine the one providing the lowest maximum tolerable power. For example, aeronautical pulse interference due to DME/TACAN systems are flight level and geographically dependent.

Moreover, note that the worst-case scenario will be determined by the combination of all the parameters impacting C_{max}, not just the aeronautical environment. In fact, the determination of the maximum power, C_{max}, of the non-aeronautical interference sources aggregate that can be tolerated depends on the targeted signal, aeronautical interfering scenario and the basic signal processing function as detailed below:

a) Each signal has its own characteristics such as power, signal bandwidth, etc.
b) Aeronautical interfering scenario determines the amount of aeronautical interference source impact being observed (DME/TACAN, JTIDS/MIDS, etc., fight level, geographical position)
c) Interfering scenario also determines some aeronautical GNSS receiver parameters such as the GNSS antenna gain
d) Each basic signal processing function has a different C/N_0 threshold
e) Each basic signal processing function usually implements a different coherent integration time, T_I, which impacts the SSC between the non-aeronautical RFI source aggregate and the PRN local replica signal

Therefore, the fundamental idea behind the GNSS RFI mask derivation methodology is the following: individual analyses must be conducted for each pair signal/function found in a given aeronautical interference scenario, and the lowest derived power among the powers derived from all pairs and scenarios will set as C_{max}.

3.B) Fundamental Steps

Following the fundamental idea presented in the previous section, derived from the fact that C_{max} depends on several elements/factors, the fundamental steps of the GNSS RFI mask derivation methodology are given below:

1) To determine basic signal processing functions thresholds
2) To determine the link margin for each pair signal/function, $u_{marg-link,sig-func}$ in its worst aeronautical interfering scenario without considering non-aeronautical RFI
3) To calculate the $I_{0,non-aero,sig-func}$ associated to each pair signal/function in its worst aeronautical interfering scenario
4) To calculate the maximum additional interference power from non-aeronautical sources, $C_{max,sig-func}$, from $I_{0,non-aero,sig-func}$ for each pair signal/function in its worst aeronautical interfering scenario.
5) To determine the maximum tolerable overall power, C_{max}, from the maximum power from each pair signal/function, $C_{max,sig-func}$, in its worst aeronautical interfering scenario.

The previous steps are detailed in the following section

3.C) Detailed Methodology

3.C.1) Step 1 - Thresholds determination

For each signal processing basic function, one or more than one threshold can be defined. The thresholds are defined from the translation on signal processing basic functions of high-level requirements of the airborne GNSS receiver nominal performance. For example, for acquisition, the threshold is derived from the high-level requirement of obtaining a first fix position within 5m of the equipment turn-on with an initial position uncertainty of 60 nmi and an initial time uncertainty of 1m; the avionics can be assumed to possess a valid satellite almanac (this requirement is being revisited). Another example for SBAS data demodulation comes from the requirement of having a probability of missing an alert of 10^{-8}.

A list of the thresholds associated to each signal processing basic function is given below. Note that some of thresholds may be under revision at the time of this work publication:

a) Acquisition [1][7]:
    i. 60 seconds to acquire the highest elevation satellite with a $p_{fa} = 10^{-4}$ and $p_d = 0.995$
    ii. 60 seconds to acquire the subsequence highest elevation satellites (2nd to 4th) with a $p_{fa} = 10^{-4}$ and $p_d = 0.995$

b) Code delay tacking [7]: a maximum RMS tracking jitter (with carrier phase smoothing) equal to 0.7m (error budget for CAT I)

c) Carrier phase tracking:
    i. Loss of lock [7]
    ii. A maximum cycle slip rate of 10^{-5}/s [1][7]

d) Demodulation [1][7]:
    i. For GPS: Word Error Rate, WER, (or subframe error rate) equal to 10^{-3}
    ii. For SBAS: Word Error Rate, WER, (or message error rate) equal to 10^{-3}

The numerical value of each threshold must be derived as a function of the analyzed signal structure as well as a function of the expected structure and quality of the airborne GNSS receiver.

3.C.2) Step 2 - Link margin calculation

The link margin calculation is usually conducted by fulfilling the Table I template. Note that the objective of this table is to express the link margin without considering non-aeronautical RFI. Therefore, the derived link margin will indeed correspond to the maximum decrease of $N_{0,eff}$, due to the presence of the aggregate of non-aeronautical RFI sources, which can be tolerated.

Table I must be interpreted as follows. In this table the middle column describes the parameter which numerical value must be provided in the right column. In this template, instead of the numerical value, a short explanation, formula, or reference on how to obtain this numerical value is provided. Note that this template has been customized for L5/E5a frequency band since lines 10 and 11 express the bdc and R_I parameters due to pulsed aeronautical interference.

Moreover, note that in line 12, in addition to calculate $N_{0,eff}$ due to aeronautical RFI sources and AWGN only, there is an uncertainty margin of 1dB that is added. The objective of the introduction of this uncertainty margin is to reduce the final power, C_{max}, to be allocated to the non-aeronautical RFI sources. The reason for adding this margin is to account for uncertainties on the evaluation of the aeronautical RFI sources impact. Remember that the calculation of bdc and R_I is very complex due to the presence of a non-linear element, the blanking mechanism, and that overbounded approximations are used [3]. Moreover, this margin also covers potential uncertainties of the $I_{0,aero,wb}$, especially for the I_{GNSS} and the potential future evolution of the systems (e.g. addition of new satellites).

An important remark of Table I is found in line 15 where the link margin is finally derived. In order to correctly calculate the link margin, $C/N_{0,eff}$ and $C/N_{0,th}$ must be consistent: since basic signal processing function can potentially be applied to only one component (e.g. carrier phase tracking should only be conducted on the pilot component of GPS L5), $C/N_{0,eff}$ and $C/N_{0,th}$ must be expressed with respect to the same component or with respect to the total signal. Usually, they are expressed with respect to the total signal.

Table I: Link margin calculation template

Line	Parameter	Value
1	Minimum received power of the total signal from the SV	From SARPS/ICD
2	Minimum antenna gain	From aeronautical interfering scenario (satellite position, flight level, receiver, antenna MOPS 373 [8])
3	Implementation losses	Calculated from targeted signal and SARPS/ICD
4	Recovered satellite power C	(1)+(2)-(3)
5	Thermal noise PSD N_0	RTCA MOPS [1][7]
6	Equivalent noise of aeronautical interference $I_{0,aero}$	Specific Study or MOPS [7]
7	Equivalent noise of avionics radiated interferences $I_{0,case\ em}$	Specific Study or MOPS [7]
8	Equivalent noise of interference of other GNSS satellite transmitting within the same band $I_{0,GNSS}$	[6]
9	Total wideband equivalent continuous RFI PSD $I_{0,\text{aero,wb}}$	(6)+(7)+(8)
10	Blanker Duty Cycle (%) (DME/TACAN, JTIDS/MIDS, SSR)	[3][4][5]
11	Pulsed interference R_I (DME/TACAN, JTIDS/MIDS, SSR)	[3][4][5]
12	Effective N_0 (dBW/Hz) with DO292 SSR and DME Interrogators (includes an extra 1dB to take into account BDC and R_I uncertainties); $N_{0,eff1dB}$	$N_{0,eff} = \frac{1}{(1-bdc)}\left(N_0 + \frac{I_{0,aero,wb}}{N_0} + R_I\right)$ $N_{0,eff,1dB}^{dB} = N_{0,eff}^{dB} + 1dB$
13	Receive carrier to noise density ratio, $C/N_{0,eff,1dB}$	(4)-(11)
14	C/N_0 operation threshold of the total signal	Methodology step 1
15	Link Margin, $u_{marg-link,sig-func}$	(14)-(13)

3.C.3) Step 3 - $I_{0,non-aero,sig-func}$ calculation

The calculation of $I_{0,non-aero,sig-func}$ should be quit straight forward from equation (12). However, due to the introduction of the uncertainty margin, its derivation becomes not trivial. The main issue about the inclusion of the uncertainty margin is how it should be used once the non-aeronautical RFI sources are included in the link budget.

Note that in Table I, the uncertainty margin is added to the $N_{0,eff}$. This means that when $N_{0,eff}$, with the non-maximum tolerable aeronautical sources power, is recalculated, this 1dB could also be added to obtain the $N_{0,eff,1dB}$ from which the final $C/N_{0,eff,1dB}$ is calculated; and thus the new final link margin should be, by definition 0. However, by doing so, this 1dB will also provide an uncertainty protection to the non-aeronautical RFI sources which is not a priori required. Therefore, this method is conservative. This is the method used in RTCA DO-292 [1] and it is mathematically expressed below:

$$I_{0,non\_aero,sig-func} = 10^{(N_{0,eff1dB}-1dB)/10} \cdot \left(u_{marg-link,sig-func} - 1\right) \cdot (1 - bdc) \tag{13}$$

A less conservative method is being proposed during the elaboration of this work at RTCA and at ICAO level. This method proposes to add the 1dB margin only on the aeronautical RFI sources plus the noise. The main issue about this proposal is that, as shown in equation (12), the $I_{0,non\_aero,sig-func}$ is modified by the $(1 - bdc)$. Therefore, is not possible to completely separate the non-aeronautical RFI sources contribution from the aeronautical RFI sources contribution (in terms of bdc).

In this work, it has been chosen to present the methodology presented in in RTCA DO-292 [1] and mathematically expressed in (13). Nevertheless, note that the presented methodology can be adapted without further modifications by using the less conservative expression of $I_{0,non\_aero,sig-func}$ (not provided in this paper) instead of equation (13).

3.C.3) Step 4 - $C_{max,sig-func}$ calculation

Once the $I_{0,non\_aero,sig-func}$ has been derived, the $C_{max,sig-func}$ can be calculated by using the relationship given in equations (9) and (10). Therefore, $C_{max,sig-func}$ is calculated from:

- Maximum equivalent noise PSD allowed to the non-aeronautical interferences, $I_{0,non-aero,sig-func}$,
- Non-aeronautical normalized baseband interference PSD, $\bar{S}_{interf,BB}$ → PSD is assumed rectangular [1][7] and thus it only depends on its bandwidth, BW
- Frequency offset, Δ_f, between GNSS/SBAS signal and interference signal carrier frequencies
- SSC between $\bar{S}_{interf,BB}$ and the normalized PRN code local replica of the inspected constellation PSD, $\bar{S}_{cm,L}$.

Therefore, $C_{max,sig-func}$ as a function of BW and Δ_f can be calculated as:

$$C_{max,sig-op}(\Delta_f, BW) = \beta_0 . \frac{I_{0,non-aero,sig-func}}{SSC_{rec}^{max}\,(\Delta_f, BW)} \tag{14}$$

Note that in order to find the maximum power $C_{max,sig-func}$, the highest SSC must be searched for among the SSC associated to each PRN code local replica of a given constellation. Each PRN local replica signal has its own PSD which can present a different worst SSC as a function of Δ_f and BW. This notion is expressed in equation (14) with the $SSC_{rec}^{max}\,(\Delta_f, BW)$ term, which expression is given below:

$$SSC_{rec}^{max}(\Delta_f, BW) = \max_{m\,\in\,total\,number\,of\,sats} \frac{1}{BW} \int_{-BW/2+\Delta_f}^{BW/2+\Delta_f} \left|H_{RF,BB}(f)\right|^2 \cdot \bar{S}_{cm,L}(f) \cdot df \tag{15}$$

There is another parameter, which is not directly expressed in equations (14) and (15), which also determines C_{max}; this parameter is the coherent integration time, T_I, of the GNSS receiver which, in its turn, depends on the GNSS basic signal processing function, acquisition, tracking or demodulation and on the signal (constellation). The influence of T_I is observed in the shape of the PRN code local replica as seen below.

$$\bar{S}_{cm,L}(f) = |\bar{C}_m(f) * \bar{H}_{ID}(f)|^2 \tag{16}$$

$$\bar{H}_{ID}(f) = \sqrt{T_I}.sinc(\pi.f.T_i) \tag{17}$$

Where:

- $\bar{C}_m(f)$ is the normalized in power FT of a pure PRN code signal (spectral rays).
- $\bar{H}_{ID}(f)$ is the normalized integrate and dump (I&D) filter transfer function

Therefore, the spectral coefficient presented in equation (15) will also depend on the coherent integration time, T_I, in addition to Δ_f and BW.

$$SSC_{rec}(\Delta_f, BW, T_I) = \frac{1}{BW} \int_{-BW/2+\Delta_f}^{BW/2+\Delta_f} |H_{RF,BB}(f)|^2 \cdot (|\bar{C}_m(f) * \bar{H}_{ID}(f)|^2) \cdot df \tag{18}$$

Influence of T_i on the normalized PRN code local replica PSD is shown in Figure 7. This figure shows the evolution of $\bar{S}_{cm,L}(f)$ for several values of the integration time for GPS L1 C/A PRN1. From this figure, it can be observed that a shorter T_I will spread more evenly the PSD (continuous PSD) while a longer T_I will make the PSD more similar to a pure periodic signal (discrete PSD). Therefore, RFI signals with narrow bandwidth (and the same power as a RFI signal with a larger bandwidth) will impact more basic signal processing functions which implement longer T_I such as tracking.

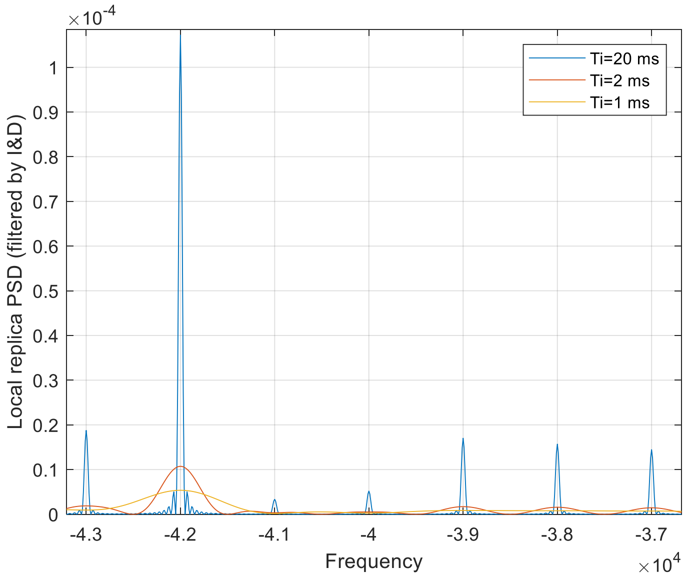

Figure 7: Local replica PSD filtered by the integrate and dump filter

Finally, it can thus be set that $C_{max,sig-func}$ will depend on the interference bandwidth, BW, interference frequency offset, Δ_f, and the coherent integration time, T_I.

$$C_{max,sig-func}(\Delta_f, BW, T_I) = \beta_0 . \frac{I_{0,non-aero,sig-func}}{SSC_{rec}^{max}(\Delta_f, BW, T_I)} \tag{19}$$

4) INITIAL RESULTS FOR RFI GNSS L5/E5A MASK

In this section the methodology presented in the previous section is used to derive L5/E5a GNSS RFI masks. Note that these derived masks cannot be the same as the final RFI masks to be presented at ICAO level. The reason for this is the potential use of a less conservative method to derive $I_{0,non-aero,sig-func}$, the potential revision of some numerical number used to fulfill Table I to calculate the link margin as well as the potential modification of the IF/RF/antenna equivalent filter presented in Figure 4 by a more constraining one (pending on manufacturers revision at RTCA level) among other potential reasons.

4.A) Threshold derivation

Table II presents the thresholds used for the L5/E5a mask derivation. Note the these threshold values were not derived in this work but were recovered from RTCA DO292 [1]. The threshold values are provided with respect to the total power of the signal.

Table II: L5/E5a basic signal processing thresholds

Function	**Acquisition, 1st Satellite, ground (2000 correlators)**	**Acquisition, 2nd -4th Satellite, en-route (400 correlators)**	**GPS : tracking, data demodulation, rising satellite acquisition**	**SBAS: tracking, data demodulation**
Threshold	29.3 dB-Hz	28.3 dB-Hz	27 dB-Hz	30dB-Hz

4.A) Link margin calculation

Table III presents link margin calculations for some signal/function pairs. For all the presented calculations as well as for the not presented ones, the worst-case scenario is found over the US hot sport near Harrisburg. The exact locations are given in the table. Note that the European hot spot near Frankfurt provides slightly better results than the US hot spot.

The results presented here correspond thus to an airborne GNSS receiver located near Harrisburg at a flight level 400feet which has been shown to provide the highest degradation in terms of DME/TACAN transponders in view [4]. The blanking threshold has been set to -121dBW; nevertheless, a blanking threshold equal to -120dBW has shown to provide almost the same performance in terms of RFI signal resistance.

Table III: L5/E5a link margin calculations

Line	**Parameter**	**SBAS L5/E5a demodulation**	**GPS L5 / tracking**	**Galileo E5a / tracking**
1	Minimum received power from the SV	-158 dBW	-154.9	-155.9
2	Minimum Rx antenna gain	0.08 (2nd highest SBAS GEO) US hot spot [40.8,-75.6]	-4.5 (5° elev angle) US hot spot [40.7, -75.55]	-4.5 (5° elev angle) US hot spot [40.7, -75.55]
3	Implementation losses	1.6	1.2	1.4
4	Recovered satellite power C	-159.52 dBW	-160.6 dBW	-161.8 dBW
5	Thermal noise PSD N_0	-200 dBW/Hz	-200 dBW/Hz	-200 dBW/Hz
6	Equivalent noise of avionics radiated interferences $I_{0,case\ em}$	-207.23 dBW/Hz	-207.23 dBW/Hz	-207.23 dBW/Hz
7	Equivalent noise of interference of other GNSS satellite transmitting within the same band I_{GNSS}	-203.22 dBW/Hz	-203.22 dBW/Hz	-203.22 dBW/Hz
8	Total aeronautical wideband equivalent continuous RFI PSD $I_{0,WB}$	-201.77 dBW/Hz	-201.77 dBW/Hz	-201.77 dBW/Hz
9	Blanker Duty Cycle (%) (DME/TACAN+JTIDS/MIDS, SSR, DMEint)	0.6582	0.6583	0.6583
10	Pulsed interference R_I (DME/TACAN+ JTIDS/MIDS, SSR, DMEint)	0.8152	0.8155	0.8155
11	Effective N_0 (dBW/Hz) with DO292 SSR and DME Int. (includes an extra 1), $N_{0,eff1dB} = N_{0,eff} + 1dB$	-191.39 + 1 dB = -191.39 dBW/Hz	-191.39 + 1dB= -190.39	-191.39 + 1dB= -190.39
12	Receive carrier to noise density ratio $C/N_{0,eff}$	30.87 dB/Hz	29.79 dB/Hz	28.59 dB/Hz
13	C/N_0 Threshold	30 dB/Hz	27 dB/Hz	27 dB/Hz
14	C/N_0 Margin	0.87 dB	2.79 dB	1.59 dB

The first conclusions that can be subtracted from Table III is that the SBAS L5/E5a signal / demodulation function is the weakest link margin pair and thus it is the main candidate to drive the L5/E5a mask derivation. Nevertheless, since the T_I associated to the demodulation function is 2ms in comparison to the 20ms of the GPS L5 tracking function, this previous statement can still vary.

Moreover, it can also be observed from the table that the $C/N_{0,eff}$ alone is not a sufficient indicator of the RFI impact: SBAS L5/E5a signal present the highest $C/N_{0,eff}$ but also requires the highest $C/N_{0,th}$, and thus presents the lowest link margin.

Finally, note that in Table III, the $I_{0,SATCOM}$ has not been included. The main reason for this exclusion in this work is that, at the moment of its publication, some elements of the model used to evaluate its impact may need further validation (e.g. coupling factor).

4.B) $I_{0,non\_aero,sig-func}$ and T_I impact on $C_{max,sig-func}$ calculation

Table IV presents the $I_{0,non\_aero,sig-func}$ numerical values from all the relevant different signal/function pairs. This derivation was conducted by applying equation (13), which corresponds to the application of the conservative method. Note that equation (13) does not take into account any characteristics of the RFI source or the T_I and thus, as expected, the lowest $I_{0,non\_aero,sig-func}$ is still provided by the SBAS L5/E5a signal.

Table IV: $I_{0,non\_aero,sig-func}$ calculations

Signal/Function	SBAS L5/E5a Demodulation	GPS L5 Dem/tracking	Galileo E5a Dem/tracking	GPS L5 Acquisition	Galileo E5a Acquisition
$I_{0,non\_aero,sig-func}$	-202.58 dB/Hz	-196.51 dB/Hz	-199.60 dB/Hz	-196.71 dB/Hz	-199.91 dB/Hz

The final $C_{max,sig-func}$ will then be computed by evaluating equation (19). From this equation, the $I_{0,non\_aero,sig-func}$ is provided in Table IV and thus, what remain is the evaluation of the β_0 and SSC terms which depends on the RFI carrier frequency offset with respect to $L5$ frequency ($\Delta_f = f_c - f_{L5}$), on the RFI signal bandwidth BW and on the coherent integration time, T_I, of the basic signal processing function. Figure 8 provides this information for an RFI signal bandwidth between 10Hz and 40MHz, and for a variation of the RFI signal carrier frequency as indicated in equation (1).

From Figure 8, it can be seen that, as expected, for narrow RFI signals bandwidths, $BW \leq 1MHz$, the basic signal processing functions using small T_I (e.g. 1ms for acquisition) are more inherently resistant to RFI impact. Moreover, it can be seen that the worst-resistant inherently signal/function is the GPS L5 tracking even though a Newman-Hoffman secondary code is implemented. In fact, it can be seen that Galileo overlay codes appear to do a better job than GPS overlay codes. For RFI signals with bandwidths higher than 1MHz, there is no significant difference between the inherent resistant of any signal/function pair.

Finally, SBAS L5/E5a / demodulation function presents the second worst case. Therefore, from this observation and from the values of Table IV, it can be predicted that the in-band/near-band RFI masks will be derived from the SBAS L5/E5a / demodulation function pair.

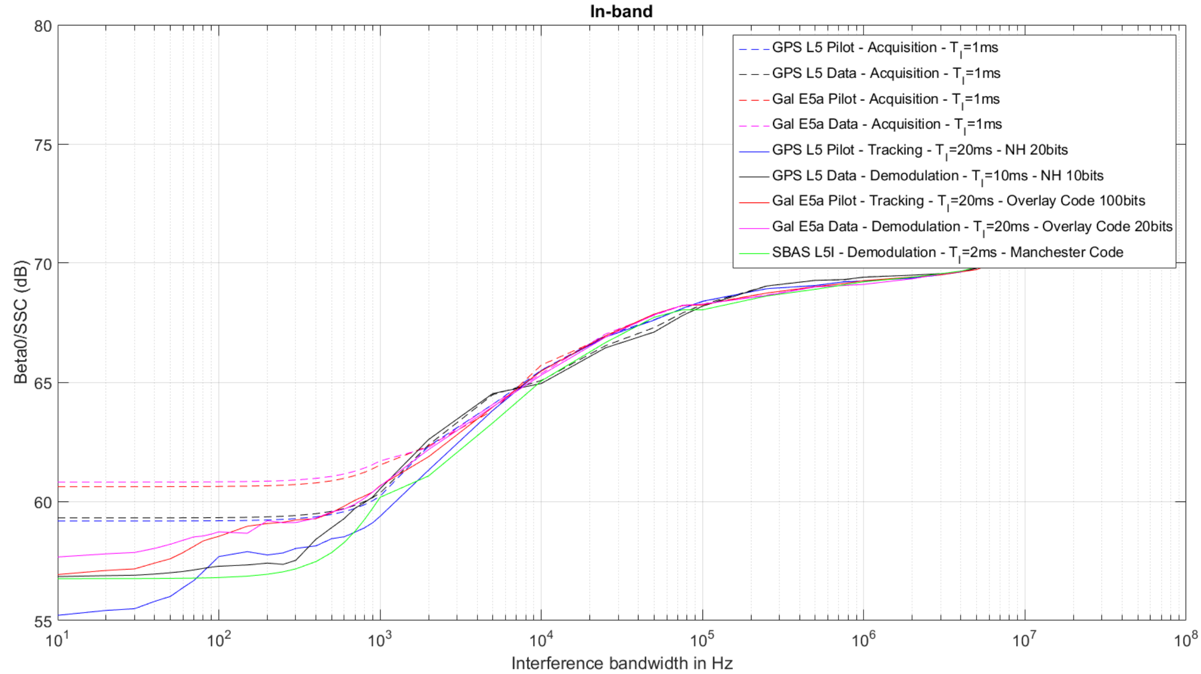

Figure 8: Local replica PSD filtered by the integrate and dump filter

4.C) In-band/Near-band and Out-of-band RFI GNSS L5/E5a Mask

Figure 9 presents the in-band/near-band maximum tolerable powers for each relevant L5/E5a signal/function pair (except for acquisition which provides higher values at narrow band frequencies). These curves have been calculated by simply adding Table IV results to Figure 8 lines (which is equivalent to equation (19)). From this figure, it is finally possible to conclude that the L5/E5a RFI masks are derived from the SBAS L5/E5a / demodulation pair. The in-band/near-band mask is also plotted in black. Note that the in-band/near-band mask is defined with monotonic linear segments, from the theoretical maximum value plotted in green, to facilitate is formal writing in table as well as its reading (table expressions are given in [9]). Note that additional extra margin is given when extrapolating the mask from the theoretical maximum tolerable power values. The in-band/near-band mask must be interpretated as the example given in Figure 1.

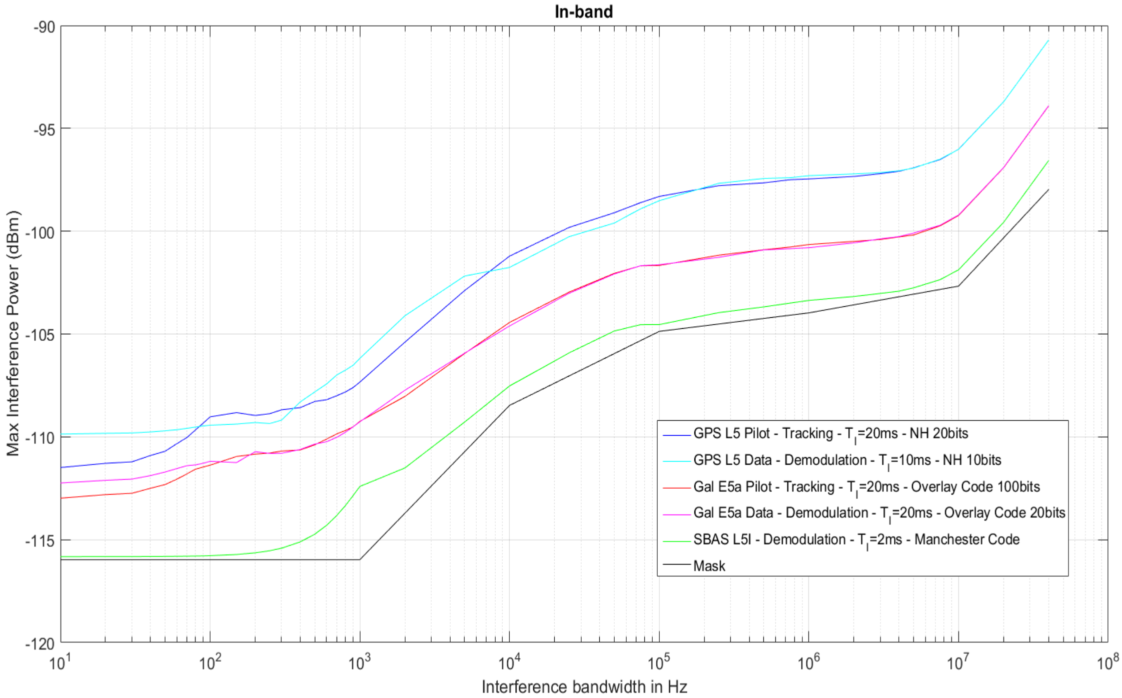

Figure 9: L5/E5a GNSS in-band/near-band RFI mask

After defining L5/E5a in-band/near-band RFI mask, the L5/E5a out-of-band RFI mask can be defined. Figure 10 presents the maximum tolerable power for a CW-like RFI source with a bandwidth equal to 1kHz and with a varying carrier frequency (expressed in the figure axis-X). Moreover, Figure 10 also presents the final L5/E5a out-of-band RFI mask, defined with monotonic linear segments, which has been extrapolated from the theoretical maximum tolerable power values. In addition, note that to keep consistency with the L5/E5a in-band/near-band RFI mask, the maximum power of the L5/E5a out-of-band RFI mask inside the L5/E5a band (20MHz as defined by the RF/IF/antenna equivalent antenna filter in Figure 4), has been set to the same maximum power at 1kHz in the L5/E5a in-band/near-band RFI mask.

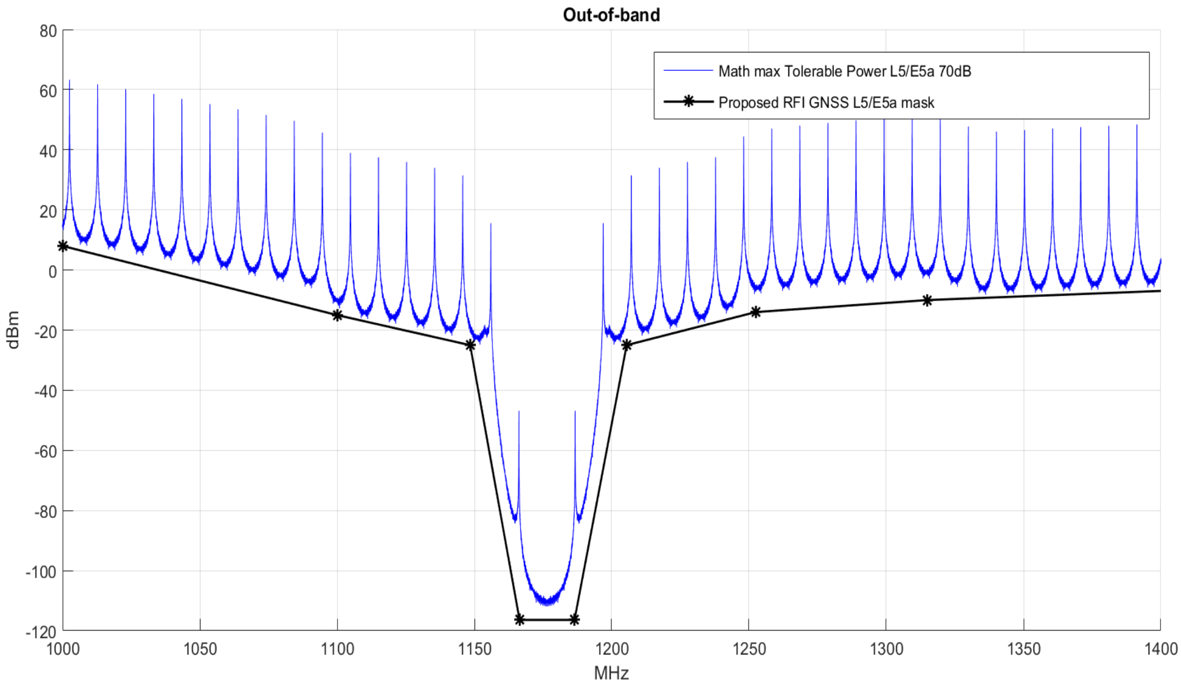

Figure 10: L5/E5a GNSS out-of-band RFI mask

CONCLUSIONS

A long series of scientific publications have presented to revisit several aspects of the RFI impact on the airborne GNSS receiver. The main objective was to define for the first time, L5/E5a GNSS RFI masks. This long series of publications are culminated with this work where the concept of RFI GNSS mask has been reminded and the methodology used to derive these masks have been provided. This methodology will be used to derive L5/E5a GNSS RFI masks or interference thresholds to be published in different aviation standards such as ICAO SARPS and RTCA/EUROCAE MOPS (RTCA DO-292 update). The only pending refinement is to determine at RTCA and ICAO level which methodology for the $I_{0,non-aero}$ derivation is the best candidate.

The GNSS RFI mask has been defined as the maximum tolerable power by the aeronautical GNSS receiver at its antenna port from non-aeronautical sources aggregate which still allows the receiver to conduct nominal operations without degraded performance. The RFI GNSS mask has been shown to define the maximum tolerable power as a function of the interference signal bandwidth and carrier frequency offset with respect to aeronautical navigation signal carrier frequency.

It has also been shown that the non-aeronautical interference signal impact is mathematically modelled as an AWG noise-like term with a PSD denoted as $I_{0,non-aero}$, and thus it is modelled as an increase of the effective N_0 observed at the correlator input. The maximum tolerable $I_{0,non-aero}$ has then been defined as the $I_{0,non-aero}$ which increases $N_{0,eff}$ so that the link margin, the difference between link budget C/N_0 and signal processing function threshold, is equal to 0. The maximum tolerable power can then be derived from $I_{0,non-aero}$ and from the Spectral separation Coefficient between the PRN local replica signal and the inspected interference PSD (modelled as a square PSD signal).

The $I_{0,non-aero}$ value is shown to depend on the targeted signal, the interference environment and on the basic signal processing function. The link between $I_{0,non-aero}$ and the maximum tolerable power is also shown to depend on the signal/function pair where the coherent integration time associated to the function has a predominant role for narrow band interfering signals.

Taking into account the previous two dependences, RFI GNSS mask derivation methodology fundamental idea was described, and its 5 steps were detailed. The methodology consisted in inspecting each signal/basic processing signal function pair to determine the one which provides the lowest maximum tolerable power.

Finally, the presented methodology was used to derive In-band/Near-band and out-of-band RFI GNSS L5/E5a masks. It was seen that this mask is derived by an aeronautical interfering scenario situated at the US hot spot (near Harrisburg) at a flight level 400. A blanking threshold set to -121dBw was used in this environment. The SBAS L5/E5a signal / data demodulation function was shown to drive the RFI masks derivation.

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