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▶ To cite this version:

Jean-Luc Issler, Lionel Ries, Jean-Marie Bourgeade, Laurent Lestarquit, Christophe Macabiau. Probabilistic approach of frequency diversity as interference mitigation means. ION GNSS 2004, 17th International Technical Meeting of the Satellite Division of The Institute of Navigation, Sep 2004, Long Beach, United States. pp 2136-2145. hal-01022450

HAL Id: hal-01022450
https://hal-enac.archives-ouvertes.fr/hal-01022450

Submitted on 30 Oct 2014

Probabilistic approach of frequency diversity as interference mitigation means

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BIOGRAPHY

Jean-Luc Issler is head of the Transmission Techniques and signal processing department of CNES, whose main tasks are signal processing, air interfaces and equipments in Radionavigation, Telecommunication, TT&C, High Data Rate TeleMetry, propagation and spectrum survey. He is involved in the development of several spaceborne receivers in Europe, as well as in studies on the European RadioNavigation projects, like GALILEO and the Pseudolite Network. With DRAST, he represents France in the GALILEO Signal Task Force of the European Commission. He invented the probabilistic theory of interference mitigation using frequency diversity, presented in this paper.

Lionel Ries is a Navigation Engineer in the Transmission Techniques and signal processing department, at CNES since June 2000. He is responsible of research activities on GNSS2 signal, including BOC modulations and GPS IIF L5. He is involved in the GALILEO program, in which he supports ESA, EC and GJU, through the GALILEO Signal Task Force. He graduated in 1997 from the "Ecole Polytechnique de Bruxelles", at Brussels Free University (Belgium), in 1997, and received a M.S. degree from the "Ecole Nationale Superieure de l'Aeronautique et de l'Espace (Supaero)" in Toulouse (France) in 1998.

Christophe Macabiau graduated as an electronics engineer in 1992 from 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 the ENAC since 2000.

Laurent Lestarquit is a Navigation Engineer in the Transmission Techniques and signal-processing department, at CNES since december 1996. He is responsible of the GNSS2 navigation payload demonstrator at CNES, also involving Lionel Ries and Joel Dantepal. He has been collaborating to several projects related to GPS space receivers (HETE2 and DEMETER) and is now involved in the GALILEO program and supports EC and ESA through the GALILEO Signal Task Force. He invented the ALTBOC 8PSK signal proposed for GALILEO in E5.

Jean-Marie Bourgeade was at CNES responsible of a study on vulnerability assessment of an ECAC Navigation Infrastructure based on GNSS, using mitigation means [1]. He worked in collaboration with Lionel Ries and Jean-Luc Issler for this study, performed on request of Eurocontrol in the frame of a contract. Jean-Marie Bourgeade is now involved in key aspects of strategical space programs with CNES.

ABSTRACT

This paper will show how frequency diversity improves the availability of accurate navigation solution of GNSS receivers, in the case of aeronautical applications for instance. Therefore, frequency diversity is a mean to mitigate jamming and interferences, to consider among others. It is very important for civil aviation to handle a probabilistic theory related to involuntary jamming of GNSS receivers, with and without the use of frequency diversity.

As a preliminary hypothesis, we assume that the GNSS link budgets has been equally balanced for each considered band Bi, even if a band is provided with more interferers than an other. In this later case, this would mean that the GNSS power is higher in the band provided with more interferers. This first assumption can be translated in probabilistic terms. The second assumption made is a jamming

probability much smaller than 1. These assumptions are used to derive:

- The probability to lose the navigation solution of a monosystem dual frequency receiver, like a L1/L5 GPS or GALILEO receiver.

- The probability to lose the navigation solution of a monosystem tri-frequency receiver, like a L1/L2/L5 GPS receiver or a GALILEO E5a/E5b/L1 or E5b/E6/L1 receiver.

An application is computed, for a jamming probability of 1/10000 during a full flight. In such a case, the probability to loose the dual frequency navigation function is 15000 times lower in the case of a tri-frequency monosystem receiver instead of a dual frequency monosystem receiver, and this makes this event an improbable case.

Intermediate conclusions has been drawn :

Frequency diversity has an enormous potential as an interference mitigation mean, which can be at least as efficient as beam forming reception GNSS antennas.

- To have an efficient ionospheric correction, the availability of two frequencies among a single system is necessary

- The use of $L1_{C/A}$, L2C, and L5 is interesting for a more robust GPS receiver. The L2C channel can be considered as a backup ; L2C is the mitigation mean.

- The use of E5a, E5b, and $L1_{BOC(1,1)}$ is also very interesting for an aeronautic GALILEO receiver, since all these 3 bands are ARNS. The E6 Galileo frequency (provided with integrity) could even be a backup to one E5 signal componant if necessary. The capability to process ionospheric corrections using only E5a and E5b GALILEO signal componants will be discussed, thanks to code/carrier divergence observations.

The paper will also show that E5b C/No degradation due to military radar spurious is low and acceptable.

INTRODUCTION

The first section will show how frequency diversity improves the availability of accurate navigation solution of GNSS receiver. Therefore, frequency diversity is a mean to mitigate jamming and interferences, to consider among others sources of failure to a navigation service.

For exemple, this fact was taken into account by the Europen Commission in its highest level communications on the GALILEO program, where “specific GALILEO frequencies”, in addition to GPS/GALILEO common frequencies, are specified “to avoid common mode of failure” due to unitentional interferences. This top level specification explain why E5b and E6 GALILEO bands will be used in addition to E5a/L5 and E2/L1/E1 GALILEO/GPS common bands. This specification is valid for each of the 4 GALILEO navigation services, and in particular for the Safety Application Service (SAS), also called Safety Of Life (SOL) Service. This is shown hereafter, in a representation of the GALILEO signal plan, compared to GPS IIF signal plan (fig 1). It has to be noted this signal plan is preliminary, and doesn’t take into account the multiplexing schemes of GPS IIF and GALILEO, and signal consolidations which will be adopted for GALILEO.

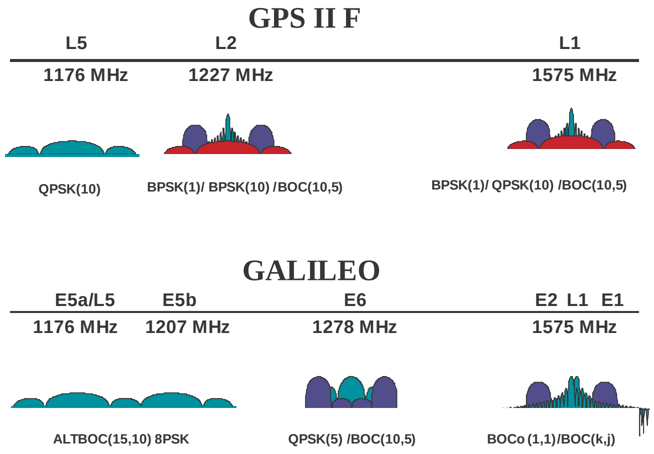

Fig 1 : GALILEO and GPS IIF signal plans

This top requirement is also the reason why the integrity message to be broadcast by GALILEO on E5 will be on E5b instead of E5a. This E5b integrity message will be broadcasted by several GALILEO satellites visible at the same time by all the airborne users. The time of arrival of the integrity bits providing from these different GALILEO satellites will be shifted one from the other, at least due to propagation delay differentials. Common mode of failures on E5b integrity bits validity could therefore be avoided.

THEORY OF INTERFERENCE MITIGATION USING FREQUENCY DIVERSITY

It is very important for civil aviation to handle a probabilistic theory related to involuntary jamming of GNSS receivers. This theory was suggested by the high level requirement mentioned in the introduction.

The risk we want to assess is the risk to lose efficient GNSS navigation, mainly in the case of a GALILEO receiver. When this risk is to be assessed, it comes naturally to mind that this depends on the number of frequency bands transmitted and their susceptibility.

First of all, under simple assumptions, it is obvious that the risk to lose all GNSS signals is larger when fewer bands are available. Therefore, we have decided to focus on the risk to lose dual frequency navigation due to jamming because that result may not be straightforward.

Dual frequency navigation capability is important, as much better performance is achieved in that case, mainly because the receiver has an efficient and safe ionospheric correction. When this capability is lost, only one frequency is remaining, and the level of performance that can be reached is only Non Precision Approach (NPA) because only RAIM with a large UERE can be run, except in the case of a GPS receiver in the regions where GPS SBAS coverage is present and not jammed.

The effect of jamming on the GNSS receiver is mainly a degradation of the true and estimated C/No in the tracking channel. If the receiver is in the tracking status, this induces globally a larger noise on the pseudorange measurement, and leading in some cases to a loss of lock on the received signal. If the receiver is in the signal acquisition phase, the useful signal does not appear so clearly among the noise, and acquisition can fail. Jamming can also sometimes lead to spoofing of the tracking channel, tracking the jammer instead of the useful GNSS signal.

In this section, we try to compute the probability for a set of specific GNSS bands to be unusable due to jamming. In the following, a GNSS band is said to be unusable when signals in this band can not be tracked, or reacquired instantly. Of course, a GNSS band can be unusable due to jamming for other reasons than simple difficulty to track (difficulty to acquire or to demodulate the signals), so these two events are not equivalent, but we are only seeking here a preliminary evaluation.

Two specific calculations will be conducted: the probability for dual frequency navigation with a single GNSS to be impossible due to jamming when 2 bands are transmitted, and the same probability when 3 bands are available.

The loss of dual frequency navigation of a single system GNSS receiver due to jamming is effective when only zero or one remaining band can be tracked, despite of jamming.

Definitions:

Let's define the following notations:

$P(ntBi)$ = Probability to **n**ot **t**rack a GNSS signal during a phase of flight, due to an involuntary jamming in the **Bi** band.

$P(tBj)$ = Probability to **t**rack a GNSS signal during a phase of flight, when there is no jamming in the **Bj** band.

Assumptions and simplifications:

To start with the theoretical formulations, we assume that the GNSS link budgets have been equally balanced for each band Bi with respect to the tracking threshold, even if a band is provided with more interferers than another. In this later case, this would mean that the GNSS power is higher in the band provided with more interferers. For instance, we can consider the L5 GPS signal, which will be transmitted with a higher power than the L1 GPS C/A code. This first assumption can be translated into probabilistic terms:

$$P(ntBi) = P(ntBj) = a$$

Therefore, we have:

$$P(tBi) = P(tBj) = 1 - P(ntBi) = 1 - P(ntBj) = 1 - a$$

$P(ntBi,ntBj)$ = jamming (not **t**racking) probability of band **Bi** and of band **Bj**

$$P(ntBi,ntBj) = a^2$$

The second assumption made is a jamming probability much smaller than 1:

$$a << 1$$

The third assumption is a total independence between the fact that signals are lost in a band Bi due to jamming, and the fact that signals are lost in band Bj due to jamming.

So we can express $P(ntBi,tBj)$, which is the probability of jamming (not **t**racking) of band **Bi** and of no jamming (**t**racking) of band **Bj** as:

$$\begin{aligned} P(ntBi,tBj) &= P(ntBi) \times [\ 1 - P(ntBj)\ ] \\ &= a \,.\, (1 - a) = a - a^2 \ \# \ a \end{aligned}$$

Loss of dual frequency GNSS navigation with a single system dual frequency receiver :

We can express the probability P(nt2,2,m) to lose the dual frequency navigation in a dual frequency single system GNSS receiver, using the fact that this happens when one, or the other, or both frequencies can not be tracked:

$$\begin{aligned} P(nt2,2,m) &= P(ntBi,tBj)+P(tBi,ntBj)+P(ntBi,ntBj) \\ &= 2.a.(1-a) + a^2 = 2.a - a^2 \ \# \ 2.a \end{aligned}$$

Therefore, everything happens like if the dual frequency navigation capability is lost as soon as one of the frequencies is lost (the probability to lose 2 bands simultaneously due to jamming is negligible).

Loss of dual frequency GNSS navigation with a single system tri-frequency receiver:

In the case of a 3 available bands Bi, Bj and Bk, we have to compute the probability $P(nt2,3,m)$ to lose the dual frequency navigation in a tri-frequency single system GNSS receiver.

This probability can be expressed as:

$$P(nt2,3,m) \\ =P(ntBi,ntBj,tBk)+P(ntBi,tBj,ntBk)+P(tBi,ntBj,ntBk) \\ +P(ntBi,ntBj,ntBk)$$

We have

$$P(ntBi,ntBj,ntBk) \\ = P(ntBi) \times P(ntBj) \times P(ntBk) = a^3$$

and

$$P(ntBi,ntBj,tBk) \\ = P(ntBi) \times P(ntBj) \times [1-P(ntBk)] = a^2.(1-a) = a^2 - a^3$$

Therefore, we have

$$P(nt2,3,m) = 3. P(ntBi,ntBj,tBk) + P(ntBi,ntBj,ntBk) \\ = 3.(a^2- a^3) + a^3 = 3a^2 - 2a^3$$

So the probability P(nt2,3,m) to lose the dual frequency navigation in a tri-frequency single system GNSS receiver is

$$P(nt2,3,m) \# 3a^2$$

Therefore, everything happens like if the dual frequency navigation capability is lost as soon as two of the frequencies are lost (the probability to lose 3 bands simultaneously due to jamming is negligible).

To check these formulas, we can compute the sum of the probabilities of all the possible events. There is a total of $2^3= 8$ possible events.

As

$$P(tBi,tBj,tBk) \\ = [1-P(ntBi)] \times [1-P(ntBj)] \times [1-P(ntBk)] \\ = (1-2a+ a^2).(1-a)$$

$$P(tBi,tBj,tBk) = 1 – 3a + 3a^2 – a^3$$

and

$$P(ntBi,tBj,tBk) \\ = P(ntBi) \times [1-P(ntBj)] \times [1-P(ntBk)] = a.(1-2a+ a^2)$$

$$P(ntBi,tBj,tBk) = a -2a^2 + a^3$$

We have well:

$$P(tBi,tBj,tBk) + 3. P(ntBi,tBj,tBk) \\ + 3. P(ntBi,ntBj,tBk) + P(ntBi,ntBj,ntBk) = 1$$

Ratio between these two probabilities:

We can express the ratio *Rp23* of the probability to lose the dual frequency navigation function with a single system dual frequency receiver, over the probability to lose the same function with a single system triple frequency receiver:

$$Rp23 = P(nt2,2,m) / P(nt2,3,m) = 2/(3a)$$

That ratio shows that, with our assumptions, if all bands have the same probability to be lost due to jamming and if these losses are independent, then having three frequencies available reduces the risk to lose dual frequency navigation by a factor roughly equivalent to the probability for a single band to be lost.

Application:

If a = 1/10000 during a full flight, we have Rp23 = 1/15000

The probability to loose the dual frequency navigation function is therefore 15000 times lower in the case of a tri-frequency single system receiver instead of a dual frequency single system receiver, and makes this event an improbable case. This is true with the equiprobability assumption expressed at the beginning of this section.

Intermediate conclusions:

Frequency diversity has an enormous potential as interference mitigation mean:

- The interest of having Bi = $L1_{C/A}$, Bj=L2C, Bk = L5 is to improve the robustness of the GPS receiver. The L2C backup is the mitigation mean.
- The interest of having Bi = E5a, Bj = E5b, Bk = $L1_{BOC(1,1)}$ is even higher for an aeronautic GALILEO receiver, since all these 3 bands are ARNS. The E6 Galileo frequency (provided with integrity) could even be a backup if necessary
- We propose to the civil aviation community to refine numerical estimation(s) of the maximum acceptable probability to lose the dual frequency GNSS navigation for every type of failure or anomaly. From these estimations, we could quantify the maximum acceptable jamming probabilities for several cases.
- We also propose to explore the cases of dual system receivers, and GPS receivers able to process overlays like EGNOS/WAAS and/or pseudolites.

Aeronautical GNSS receivers provided with a frequency diversity interference mitigation capability are also cost efficient equipments, when compared to receivers provided with electronic antijam antennas (so called CRPAs) nulling the reception gain in the directions of the interfering sources. A combination of these two techniques could even be necessary for the more critical aeronautical applications in term of safety.

NEED FOR AN IONOSPHERIC CORRECTION

It has to be noted that the use of only E5a and E5b could provide efficient ionospheric corrections for civil aviation needs when GALILEO will be in place.

Let's remind the already existing possibility to make single frequency ionospheric corrections using a Kalman filter processing code/carrier coherency measurements performed on GPS C/A codes [2], [3]. The single frequency results using GPS C/A codes only are very close to well calibrated dual-frequency measurements (fig 2, 3). Usually there are only a few decimetres (less than 30 cm.) between the both results. The measurements showned here (fig 3) are done using NR106 C/A code receivers (single frequency ionospheric error determination) and Z12 dual frequency GPS receivers (dual frequency ionospheric determination).

The measurement noise and the bias calibration efficiency will be improved with 10.23 Mcps signals in E5a and E5b. The accuracy and the robustness of the E5a/E5b ionospheric correction, combining single frequency and classical dual frequency ionospheric correction methods.

In addition, since E5a and E5b will be components of a single superwide GALILEO E5 signal spectrum, thanks to the ALTBOC(15,10) modulation [4], [5], the accurate and robust single frequency ionospheric determination proposed by B. Parkinson for GNSS2 using very wide band signals will be also possible.

Therefore, the possibility to perform dual frequency ARNS navigation using either E5a/E5b, E5a/L1 or E5b/L1 is justified.

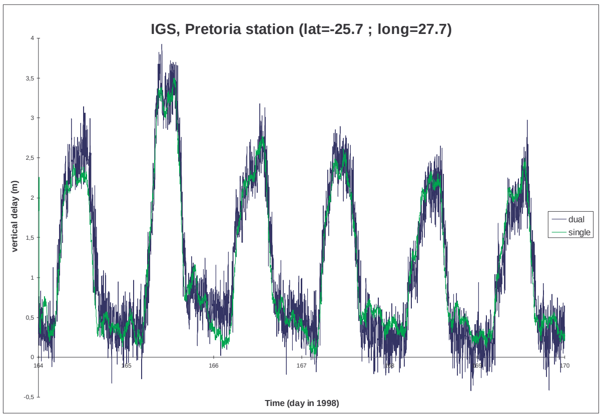

Fig. 2 : Comparison between single and dual-frequency measurement*s*

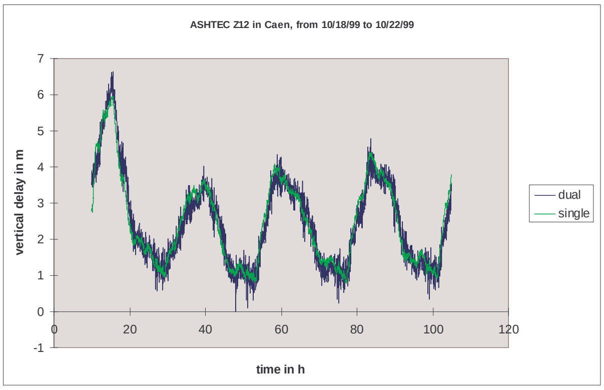

Fig. 3 : Comparison between single and dual-frequency measurements

EFFECT OF RADARS, DME AND JTIDS/MIDS ON E5a/L5 and E5b

The presence of radars in the 1215-1350 MHz band raised the question of potential degradations of GPS and GALILEO signals due to spurious interferences in the adjacent E5a/L5 and E5b frequency bands. But, we have also to take into account the degradation of the E5b GALILEO signal by the DME/TACANs [fig 4], the JTIDS/MIDS and the future GLONASS L3 signal which will use a large portion of the E5b band.

We can note that the upper DME central frequency is 1213 MHz, as shown by fig 5. Therefore, the 1213-1215 MHz upper portion of the considered ARNS-RNSS band is free of DMEs. Moreover, as it is the case in Europe, the full E5b portion of this band host less DMEs than in the E5a/L5 portion in most of the world, excepted maybe in some regions managing to realocate partly a few DME frequencies outside L5, like in the USA. Therefore, the degradation due to DME/TACAN will be generaly larger in E5a/L5 than in E5b. Moreover, since the E5b RF filtering of the future aeronautical GNSS receiver will reject frequencies above 1215 MHz, and since the E5b center frequency from a frequency management point of view is 1207 MHz , the E5b filter cannot have a bandwidth larger than 2x(1215-1207) = 16 MHz. Practically, this bandwidth will be rather not higher than 14 MHz. This bandwidth has to be compared with the one othe E5a/L5 RF filtering, which should be close to 20 MHz. Since the E5a/L5 filter is larger than the E5b filter, this reenforce a smaller degradation in E5b due to DME/TACANs, in regards to the case of E5a/L5, despite the extracorrelation losses due to the E5b filtering are taken into account.

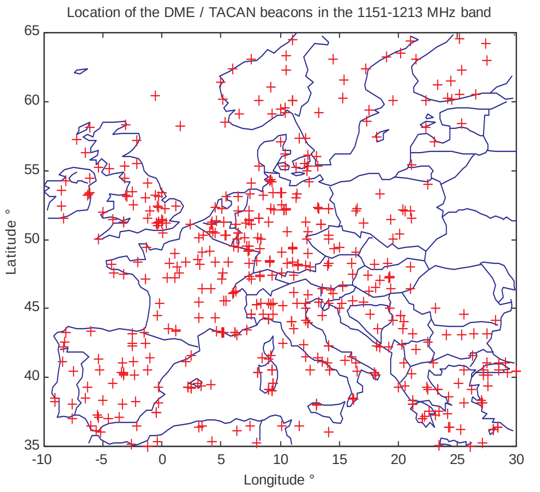

Fig 4 : The DME / TACAN beacons over Europe

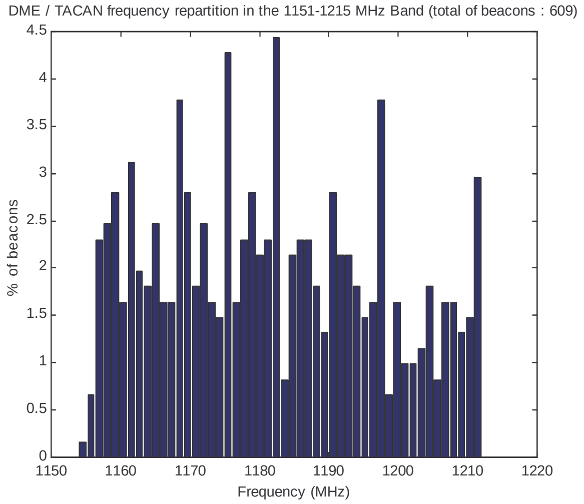

Fig 5 : Frequency repartition of the DME / TACAN beacons in X Mode, in Europe

A similar discussion can be done for the case of JTIDS/MIDS, since the GALILEO E5b central frequency is very close (1 MHz appart) from the upper JTIDS/MIDS channel (1206 MHz). This means there is no extra JTIDS/MIDS channel in the 1206-1215 MHz portion of the E5b GALILO signal. This provide to GALILEO a natural protection from the JTIDS/MIDS system and vice versa. Moreover, the E5b final frequency selection of GALILEO took into account the recommandations of the multinational JTIDS/MIDS Working Group for a maximum isolation between the 2 systems, which was well received by this Working Group, which also cares about the practical protection of JTIDS/MIDS from GNSS in all kind of situation. Other possible E5b central frequencies previously studied, like 1197, 1202 or 1204 MHz would have created a situation closer to the one of GPS L5 regarding JTIDS/MIDS, despite the partial realocation of some JTIDS/MIDS channels possibly planed in L5. For this reason, and thanks to a small E5b RF filter bandwidth, the degradation of the E5b GALILEO signal due to JTIDS/MIDS will be smaller to the one of the GPS L5 and GALILEO E5a.

We can also note than if the E5b "central" frequency would have been lower than 1207 MHz, it would have been very difficult to make E5a/L5 and E5b filter in a multistandard GPS/GALILEO receiver, provided with sufficient mutual isolation to avoid common mode of failure due to RF interferences, according to the generally admited civil aviation criterias. Moreover, if common mode of failure due to interference exists, the probabilistic theory described above is not valid, and the risk of GNSS navigation failures would increase significantly.

Let us also remind the content of a paper of FAA, Aerospace corp and MITRE corp, written at the time of the GPS L5 frequency selection [6]. This paper simply concluded that 1207 MHz (one of the last L5 candidate frequency before selection of 1176 MHz) is the best choice to have both DME and JTIDS compatibility with GNSS in the considered ARNS band.

After having showned than the main in-band interferer of E5b will create less degradation compared to the case of E5a/L5, let’s study the case of the out of band interferer creating spurious emissions in E5b and E5a/L5.

Most of the concerned radars are military radars dedicated to Air-surveillance. An important exemple of military radar, presented as a possible work case in term of interference to GNSS in E5 band [7], is the AN/TPS-59, having a peak transmited power close to 45000 Watts (46.5 dBW), and a PRF (Pulse Repetition Frequency) close to 272 pps (pulse per second) in average. This means these type of radar transmits one meta-pulse every 3.6 ms in average. Actually, different types of pulses are transmitted from this type of radar. In the measurements provided in [7], we observe meta-pulses made of 3 elementary pulses : a "leading pulse", followed approximately 100 µs later by the "middle pulse", itself followed approximately 100 µs later by a "trailing pulse". This means that 200 µs separate the leading pulse from the trailing pulse. Each elementary pulse has a duration of a few tens of ms, generally below 0.5 µs. In the measurements provided in [7], we observe a repetition period of the meta-pulse equal to approximately 1 ms, this meaning a PRF close to 1000 pps, higher than the previously mentioned average PRF value. If we assume each elementary pulse to have a 0.5 µs length, we have an equivalent duty cycle below 0.0015. With such a duty cycle and a peakpower of 45000 Watts, the average "usefull" power transmited power is below 7 Watts. However, if we assume the interpulse noise to be so high as this noise can be itself assumed to be like a saturating pulse, when the receiver is very close to the radar, we get an equivalent duty cycle of 200 µs / 1000 µs = 0.2. The reality is probably in between.

Moreover, we have to assume that the antenna patern is very narrow, since its mission is to scan progressiely a wide portion of the sky to survey. This means that the equivalent duty cycle will be reduced significantly from the point of view of an airborne user, having a low angular speed compared to the one of the radar antenna pattern. Therefore, even in the very pessimistic case of saturating interpulse noise, we can consider an equivalent duty cycle close to 0.01.

A typical spectrum of a meta-pulse transmited from an ANTPS-59 radar, shown from time to time in diverse fora like the NAVSAT 2000 convention to illustrate potential interferences with ARNS system below 1215 MHz due to military radars, is given in figure 6.

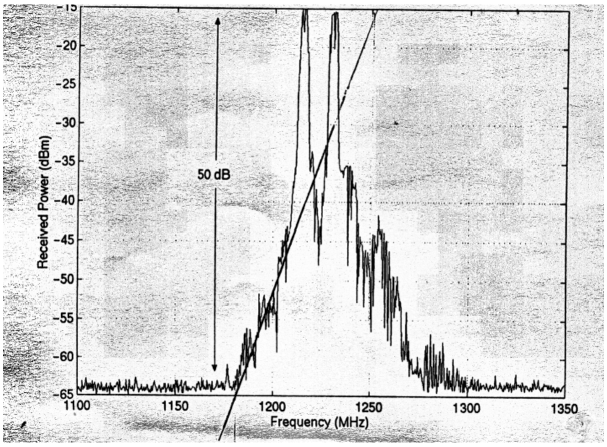

Fig 6 : Spectrum of AN/TPS 59 radar emissions sometime shown to illustrate potential interference with ARNS

This figure show the spectrum of a meta-pulse, transmitted in two frequency channels f1 and f2 [6]. Each channel corresponds to a main spectral lobe, centred on approximately 1213 MHz and 1231 MHz. The 3 dB width of each main lobe is approximately 5 MHz. The lower main lobe penetrates well below the 1215 MHz ARNS limit, with a peak power close to 45000 Watts. In such conditions, we would have from a regulatory point of view unacceptable "spurious" emissions below 1215 MHz, which would certainly lead to a frequency realocation procedure at the level of the International Telecommunication Union (ITU) if significant impact on aeronautical users is predicted. Fortunately, this is not really true, and we would be misleading by delivering only the previous informations about the military radars.

One of the main characteristics of the military radars is the generalized use of frequency hoping techniques : Each pulsed emission (or group of pulsed emissions) is transmited in a frequency slot. The switching sequence from slot to solt is an uncrypted algorithm, and the frequency range occupied by all the possible slots is the wider as possible. This is done for obvious security reasons.

For instance, each frequency slot of the AN/TPS 59 can be occupied by a so-called "frequency pair " $\mathbf{f_i/f_{i+1}}$, as shown by figure 6 for i=1 (frequency pair $\mathbf{f_1/f_2}$, with $\mathbf{f_1}$ close to 1213 MHz). The AN/TPS 59 transmit frequency pairs in 20 frequency slots, up to $\mathbf{f_{20}/f_{21}}$, with $\mathbf{f_{21}}$ close to 1400 MHz [7]. This is logical, since the considered allocated radar band is 1215-1400 MHz. The frequency range occupied by the AN/TPS 59 pulses measured in [7] is therefore 1400-1215 = 185 MHz. To maximize the uncryption efficiency and the spectrum spreading of the radar transmissions, the probability $\mathbf{P_i}$ to transmit a frequency pair $\mathbf{f_j/f_{j+1}}$ is equal to the probability $\mathbf{P_j}$ to transmit a frequency pair $\mathbf{f_j/f_{j+1}}$.

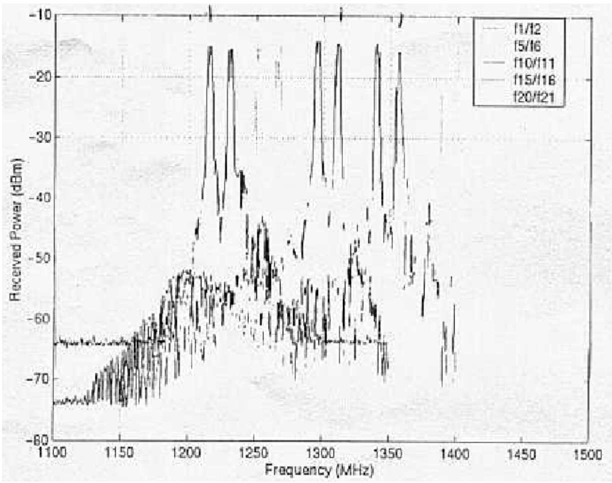

Fig 7 : Spectrum of AN/TPS 59 radar emissions showing their frequency hoping feature

This clearly show that frequency hoping feature of the military radars will reduce significantly their effects in E5a/L5 and E5b ARNS receivers. In particular, the amount of RF radar power transmited in the RF E5b filter will be significantly reduced, and the equivalent saturating duty cycle as well.

To deal with such spurious radar pulsed emissions, the GNSS L5/E5a and/or E5b receiver shall be provided with a pulse blanker (already preexisting thanks to the need to mitigate DME/TACAN and JTIDS/MIDS pulses) and with power limiting deviced located in the receiver front end (this element is also preexisting in the E5a/L5 and/or E5b processing chain designs for elementary security reasons).

We can therefore conclude than military radar transmissions are not so dramatic as sometimes "predicted". The blanking losses due to AN/TPS-59 in E5b have been computed below 0.2 dB.

Moreover, it is usefull to precise some characteristics of the E5b GALILEO spectrum, which has an updated design since the ALTBOC(15,10) modulation scheme was choosen for E5a and E5b signal elements [4], [5], [9].

This updated design might have an impact on the proposed L5/E5 intereference mask described in [8], which was designed considering a 10.23 Mcps QPSK signal with a maximum power spectral density centered on 1207 MHz, which was the previous GALILEO E5b signal baseline when the said rejection mask design was performed. With the ALTBOC(15,10) signal [4], [5], having a "sinus" square subcarrier phasing , the maximum spectral density of E5b will be centered on 1205 MHz instead 1207 MHz.

Moreover, the ALTBOC(15,10) PSD at 1215 MHz is lower than in the case of a QPSK(10) signal centered on 1207 MHz. This is due to the fact the ALTBOC-sinus signal concentrates the spectral energy rather in the inner sides of the 2 main lobes of this signal, compared to the external sides.

We recommand to study the possibility to filter the E5a band in 14 to 16 MHz, instead of 20 MHz, in order to ease the isolation required between E5a and E5b, and to decrease the global losses in E5a, mainly due to DMEs/TACANs and JTIDS/MIDS, but also to some Air Traffic Control (ATC) radars and GNSS, with a correlation loss increase significantly lower than the mentioned gained losses. This would also allow to reduce the processing power required to process simultaneously GALILEO and GPS signals. This would also permit a more symetrical interference rejection mask.

We also recommand the L5/E5 interference rejection mask to be designed using the methodology to compute C/No degradations provided in annex, with realistic pessimistic scenarii, and the required aeronautical margin. Since the impact on E5 of frequency hoping radars is reduced, the approach adopted in [8] is logically to give more consideration to civilian ATC radar to drive the interference rejection mask design.

CONCLUSIONS

We have established a probabilistic theory related to involuntary jamming of GNSS receivers. We propose the work on the probabilistic theory to be continued, and the work on the E5 degradation due to frequency hoping pulsed spurious interferences and on the E5a/L5-E5b interference mask to be detailed as well.

The probabilistic theory already proves the good performances of a cost efficient interference mitigation mean : the use of GNSS frequency diversity. It justify one of the top requirements for GALILEO presented by the European Commission, to avoid common mode of failure between GPS and GALILEO (due to unvolontary jamming of a common frequency band). We have shown the efficiency of E5a/E5b/L1 GALILEO receivers or L5/L2C/L1 GPS receivers to mitigate interferences in order to preserve an efficient and robust dual frequency navigation.

We have shown that the E5b integrity channels will be generally less degraded than E5a/L5 channels by the DME/TACANS and by the JTIDS/MIDS. We have shown than the degradation of E5b due to military radars are low and acceptables, thanks to their frequency hoping features. Therefore, the global losses due to DME/TACANS, JTIDS/MIDS, Radars and GNSS will be lower in E5b than in E5a/L5.

This confirm why GALILEO E5b will serve civil aviation, allowing to use GPS, GALILEO and related integrity channels as robust, complementary and independant systems.

ACKNOWLEDGMENTS

The authors wish to thank Willy VIGNEAU from M3SYSTEMS for his help on the probabilistic analysis, and Frederic BASTIDE for contributing to the L5/E5 band susceptibility analysis.

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ANNEX : DEGRADATION OF C/No

In this annex, we compute the degradation of the C/No ratio in the presence of pulsed and non pylsed interferences. We assume a blanker in the receiver, which set to zero all the samples above the blanking threshold.

The degradation of the usefull signal is $(1\text{-}Bdc)^2$ and the degradation of the thermal noise at the correlator output is *(1-Bdc)*, where *Bdc* is the blanker equivalent duty cycle, that is the time percentage during which the signal is blanked to zero. This percentage depend on the blanking threshold but also of the interfering pulsed power in the usefull bandwidth. The frequency hoping features of the military radar pulses are taken into account to compute this equivalent power in the usefull bandwidth. This percentage also depend on the hit ratio between the GNSS reception antenna patern mask and the scaning directive antenna patern mask of the radar. The term *(1-Bdc)* is called the blanking losses.

The contribution of the radars is also included in the term $I_{0,pulsed}$ described hereafter whose computation requires to know the spectrum and the number of the interferences. $I_{0,WB}$ does not correspond to the impact of the pulsed interference, and shall not be considered when only radar pulses and thermal noise are present.

The effective post-correlation $C/N_{0,eff}$ is

$$\frac{C}{N_{0,eff}} = \frac{(C.G_S / L_{IMP}).(1-Bdc)^2}{(1-Bdc).(N_O + I_{0,WB} + I_{0,pulsed})}$$

where

* C is the satellite power received by a unity gain circular isotropic antenna

* G_S is the GNSS antenna gain ratio (with respect to circular isotropic)

* L_{IMP} is the GNSS receiver implementation loss ratio

* *Bdc* is the blanker duty cycle

* N_0 is the GNSS receiver system thermal noise power spectral density

* $I_{0,WB}$ is the equivalent power spectral density of continuous RFI that include (1) $I_{0,WBX}$ the external continuous RFI; (2) the aeronautical margin added to $I_{0,WBX}$ and (3) $I_{0,IS}$ the intra/inter -system RFI. The tranfer function of the receiver filter is taken into account to compute this PSD.

* $I_{0,pulsed}$ is the equivalent power spectral density of pulsed RFI. The tranfer function of the receiver filter is taken into account to compute this equivalent PSD. The frequency hoping features of the military radar pulses are taken into account to compute this equivalent PSD. The hit ratio between the GNSS reception antenna patern mask and the scaning directive antenna patern mask of the radars is taken into account to compute this equivalent PSD. NB : The time of presence of a set of pulses providing from a scaning radar antenna is generally smaller than the time constant of the DLLs and the Carrier tracking loops of the GNSS receiver.

Equivalently the last expression may be written as

$$\frac{C}{N_{0,eff}} = \frac{C.G_S / L_{IMP}}{N_O} \cdot \frac{1}{\frac{1}{1-Bdc}.\left(1+\frac{I_{0,WB}}{N_0}+\frac{I_{0,pulsed}}{N_0}\right)}$$

Let define the term corresponding to pulsed interference as

$$R_I = \frac{I_{0,pulsed}}{N_0}$$

So the effective $N_{O,eff}$ equates

$$N_{0,eff} = \frac{N_0}{1-Bdc}.\left(1+\frac{I_{0,WB}}{N_0}+R_I\right)$$

yielding the following $C/N_{0,eff}$ degradation:

$$\deg\left(\frac{C}{N_{0,eff}}\right) = \frac{(1-Bdc)}{\left(1+\frac{I_{0,WB}}{N_O}+R_I\right)}$$