Interference mitigation techniques for air receivers

Sustainable Mobility and Intermodality
Promoting Competitive and Sustainable Growth

GALILEI TASK G

Interference mitigation techniques
for Civil Aviation Receivers
(G3C2-2)
Sustainable Mobility and Intermodality
Promoting Competitive and Sustainable Growth

GALILEI TASK G

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SUMMARY:

This document deals with interference mitigation techniques in order to make recommendations for future standards. First, the environment of interference is described and possible disturbing interferences are detailed. Then, interference mitigation techniques and combinations between solutions are listed. Next, interference requirements in current standards are analysed to find an adapted interference requirement for E5 band. Afterwards, a possible interference test is developed considering current and envisaged (2010-2015) interferences environment. In the final part, main simulations’ results on efficient interference mitigation techniques have been given. In conclusion, main recommendations for future standards are listed.
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EXECUTIVE SUMMARY

1.1 PURPOSE

This document presents the contribution of the task G3-C2-2 Interference Mitigation Techniques of the Work Package G3C2 Receiver study. Its aim is to overview and make a synthesis of the performances of mitigation techniques for pulsed RF interference in E5 band to determine recommendations for future standards and to support their discussion in meetings at ICAO GNSSP, EUROCAE (WG62) and RTCA SC159.

Based on simulations, the results and conclusions of the first issue of this paper are a basis for the future E5 filtering scheme standardised definition (mainly based on pulsed interference sensitivity) and its possible impact in the future RF interference error budget definition.

In this second issue, some chapters have been updated, mainly based on comments received and to point out new recommendations when needed.

Other G3C studies, such as the multiple frequencies air receiver technical note (contribution for Task G3C2-1) have proposed complementary updated results, mainly focused on interference environment and their possible impact on RF-Front-End architecture.

1.2 CONTENTS

Interference’s signals on L1 are well known and receivers are able to withstand them. The new allocated frequency, E5, is occupied by ARNS systems like DME/TACAN, JTIDS/MIDS. GALILEO receivers working with E5 will have to cope with them.

The first issue of this paper established:

- Disturbing interference in E5 band and their impact
- A list of feasible interference mitigation techniques in terms of cost and performance
- An enumeration of interference requirements existing in current standard
- Requirements which can be used in future standard in E5 band

The second issue of this paper proposes some updated chapters

- Appendix describing the FDAF techniques
- Additional technical justifications

1.3 MAIN CONCLUSIONS AND RECOMMENDATIONS

Issue 1:

- A receiver, which uses E5\textsubscript{B} and L5, shall isolate a minimum of 50dB between the two frequencies in order to ensure no common failure mode due to interference (Civil Aviation Requirements).

- A blanking technique or a FDAF technique is sufficient to ensure tracking and acquisition threshold compared to future receiver capacities.

- Acquisition of E5 signal in DME environment is a dimensioning one, but still manageable for future receivers which will benefit through technology progress of more correlators than current receiver.

- At the same time, there is a need to re-examine operational needs for acquisition in en-route navigation, as re-acquisition only with positioning from second frequency (L1) may release design constraints.
Test on the receiver shall integrate DME/TACAN case scenario. More DME/TACAN beacons than currently installed should be considered: 20% more for the 2010-2020 time frame and less after.

Standard deviations on the pseudo-range due to DME interference for different mitigation techniques have been presented. These results should be further used in an overall accuracy budget.

If VHFCOM antenna and GNSS antenna are isolated of 50dB on the plane, a 44dB-rejection filter has to be added to the VHFCOM emitter.

No deployment plan and precise characteristics of radar are given. In this context and within this limited overview, it is not possible to define realistic margins to be taken into account for radar.

**Issue 2:**

This updated issue makes only the link between the current studies, which have brought new results and consequently new possible standards recommendations:

- The interference environment update have been studied in other technical notes and working papers such as
  - Task G3C2-1 Multiple Frequencies Air Receiver technical note,
  - RTCA and EUROCAE working papers

- The impact in the future error budget should be carefully analysed, particularly in terms of
  - New pulsed interference (DME/TACAN) emitted power (increase of 6 dB) impact
  - New possible interference sources (UWB, other VHF and UHF systems, communication systems, etc.)
  - The way and conditions in which all the different interference sources (RADARs, pulsed interference, communication systems, etc.) are summed in an overall error budget, in order to be realistic enough and to avoid pessimistic standards.

**Future work**

For future standards, it is highly recommended to consolidate knowledge assumption on E5 Interference environment. The DME pulsed interference is one of the main drivers in E5 band, but has to be combined with other sources in the global budget error for RF interference susceptibility. Today, the lack of information (real pulsed interference, other communication and VHF/UHF systems standards impact, etc.) raises serious problems in terms of future air-receiver definition as it may lead to pessimistic budget and not contribute to GALILEO promotion.
2 INTRODUCTION

2.1 PURPOSE

This document presents the contribution of the task G3-C2-2 Interference Mitigation Techniques of the Work Package G3C2 Receiver study. Its aim is to make a synthesis of the mitigation techniques and their performances, to determine our recommendation for standard and to communicate them participating to their elaboration in meeting such as GNSSP and EUROCAE.

2.2 CONTENTS

Interference’s signals on L1 are well known and receivers are able to withstand them. The new allocated frequency, E5, is occupied by ARNS systems like DME/TACAN, JTIDS/MIDS. GALILEO receivers working with E5 will have to cope with them.

This paper establishes:
- Disturbing interference in E5 band and their impact
- A list of feasible interference mitigation techniques in terms of cost and performance
- An enumeration of interference requirements existing in current standard
- Requirements which can be used in future standard in E5 band
3 REFERENCES

3.1 DEFINITIONS

Hdop  Horizontal Dilution of precision
Vdop  Vertical Dilution of precision

3.2 ACRONYMS

ADC  Analogue Digital Converter
AGC  Automatic Gain Control
BER  Bit Error Probability
BPS  Bit per second
CRPA  Controlled Radiation Pattern Antenna
HF  High frequency
PRN  Pseudo Random Noise
SIS  Signal In Space
SPS  Symbol per second
TBD  To be defined
TSDF  Timeslot Duty Factor

3.3 APPLICABLE DOCUMENTS

AD2  Appendix C, DO229, 1998, RTCA.
AD3  ARINC 709A, Precision Airborne Distance Measuring Equipment (DME/P), 1987.
AD4  ARINC 568, Airborne Distance Measuring Equipment (DME/P), 1986.
AD5  DME/TACAN database OACI, provided by French Civil Aviation, STNA
AD6  International standards and recommended practices, aeronautical telecommunications, OACI.

3.4 REFERENCE DOCUMENTS

RD1  Validation of the feasibility of coexistence of the new civil GPS signal (L5) with existing system. February 2001. MITRE
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RD2  GNSSP-WG/B-WP/15 Comparison of DME/TACAN impact over several signals at 1202 and 1207 MHz over Europe, March 19th-30th , 2001, J.L.Issler, M.Monnerat, B.Roturier.


RD9  Evolution des services de radionavigation fournis aux mobiles, D Stammler, October 2000.

RD10  « Assessment of radio frequency interference relevant to the GNSS », RTCA/SC-159, January 1997

RD11  Interference analysis S074m, GAL2-ASPI-TN-198, April 2002

RD12  JTIDS/MIDS Scenarios used in GPS L5 compatibility analyses, GNSSP/WGB/SSG WP1, September 2001

RD13  Signal Task Force presentation on JTIDS/MIDS/Link16, Paul Nisner, Frebruary, 5th 2002

RD14  Compatibility between civil aviation en-route requirements on E5b and mitigation technique performances, Task F, E.Kirby, June 2002.


RD18  Methodology for assessing the sharing between the radio navigation-satellite service (space-to-earth) and the aeronautical radio navigation service (DME/TACAN) in the band 1164-1215MHz, ITU, May 2001, sub-working group 8D5B.


RD20  “Multiple frequencies air receivers”, GALILEI G3C2-1 Technical Note, THALES Avionics, Y. Ernou, April 2003

3.5 DOCUMENTS PRESENTED TO GNSSP AND EUROCAE

RD16  GNSSP Brussels, April 15th to 25th, Interference mitigation techniques for GALILEO receivers utilising the E5 signals. Working paper prepared by THALES Avionics for SAGA and GALILEI.

RD17  EUROCAE 14 may 2002 Open Issues regarding the Design of a Receiver using several independent Satellite Constellation. Working paper prepared by THALES Avionics for SAGA and task G.
4 DEFINITION OF THE INTERFERENCE ENVIRONMENT

4.1 INTERFERENCE IN E5 BAND

Major existing systems operating at or near E5 band include:

- Aeronautical systems operating between 960 and 1215MHz- including DME and TACAN systems that operate throughout the band.
- Aeronautical systems operating near the band- including Secondary Surveillance Radars (SSR), Traffic Collision and Avoidance System (TCAS), Identify Friend or Foe (IFF) and planned Automatic Dependent Surveillance-Broadcast (ADS-B).
- JTIDS/MIDS operating between 969 and 1206MHz
- Military and civil radars operating between 1215 and 1385MHz

One common characteristic of all these system is that they are pulsed.

[RD7] shows that DME/TACAN are of primary concern for E5. JTIDS/MIDS beacons are less numerous. Moreover, [RD7] simulations show that they have less influence than DME/TACAN. Tests with DME/TACAN are sufficient. Nonetheless, a margin for JTIDS/MIDS should be taken.

[RD7] shows that out-of-band radar emissions from radars operating above 1215MHz are sufficiently attenuated so as to pose negligible threat to E5a: this attenuation is assured by radar manufacturer and by the separation between E5a frequency band and the radar operating band. However, these radars may disturb E5b, which is just next to radar operating band. A margin for out-of-band radar should thus be taken.

Harmonics of VHFCOM and TV emitter can also be found in the E5b or L5 band.

4.2 DME/TACAN INTERFERENCE

4.2.1 DME/TACAN influence over the world

[RD8] gives post-correlation S/N0 degradation over the world represented on the following figure.
Theses figures indicate that DME/TACAN are not disturbing at low altitude. But they are of primary concern at high altitude.
Moreover, they point out that DME/TACAN have a large influence on Europe. A receiver, which can work correctly over Europe, can manage over the United States and Japan.

4.2.2 DME/TACAN over Europe

The numbers of beacons of DME and TACAN over Europe depending on the frequency are given on the figures above.

Figure 3: Frequency repartition of DME beacons over Europe

NB: The database used is [AD5].
The previous figures point out that E5b is currently more favourable than E5a. That is to say that a receiver, which deals with E5a interference scenario, can manage with a E5b interference scenario.

4.2.3 Worst scenario at 40000 feet in L5 frequency band
At high altitude (40000 feet), a worst scenario in L5 band over Europe is found when flying over 51°longitude and 8°latitude.
Interference mitigation techniques for air receivers

Figure 5: Beacons in view for the chosen high altitude scenario in L5 frequency band

NB: On the figure, only potentially disturbing for L5 band beacons are represented.

The power characteristics of beacons seen in this scenario are shown below:

Figure 6: Received power from DME/TACAN beacons in view for the high altitude scenario (1) in L5 frequency band

DME/TACAN received power after the antenna receiver for the 40000 feet scenario example is between –100dBW and –125dBW.

29 DME/TACAN beacons in view are emitting in the useful band.

Two others characteristics to take into account are the pulse pairs starting time and repetitions. DME pulse pairs start at random (DME systems’ principle). The maximum numbers of aircraft that can be served by a
DME/TACAN beacon is 100. If this number of aircraft is reached, the reply capability of the transmitter should be at a transmission rate of 2700 plus or minus 90 pulse pairs per second for DME and a transmission rate of 3600 plus or minus 90 pulse pairs per second for TACAN.

Remark: Annex A describes precisely DME/TACAN time and spectrum characteristics.

### 4.2.4 Worst scenario at 40000 feet in E5b frequency band

This worst scenario is taken from Task F [RD14].

At high altitude (40000 feet), a worst scenario in E5b band over Europe is found when flying over 51°longitude and 8°latitude.

**Figure 7: Beacons in view for the chosen high altitude scenario in E5b frequency band**

NB: On the figure, only potentially disturbing for E5b band beacons are represented.

The power characteristics of beacons seen in this scenario are shown below:
DME/TACAN received power after the antenna receiver for the 40000 feet scenario example is between –100dBW and –125dBW.

18 DME/TACAN beacons in view are emitting in the useful band.

4.3 RADAR INTERFERENCE

[RD10] and [RD11] have listed possible disturbing radar for GNSS receiver. The following table gives some characteristics of possible disturbing radar:

<table>
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<th>RADAR type</th>
<th>Frequency band (MHz)</th>
<th>Maximum pulse width (µs)</th>
<th>Maximum radiated power (dBW)</th>
<th>Out-of-band-specified power level (dBW)</th>
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Table 1: Selected RADAR characteristics

A fine determination of signal to noise degradation due to one of these radar is impossible with these characteristics only. Pulse shapes, repetition frequency, type of modulation, antenna directivity, and antenna rotation speed are essential to know.

Moreover, NO DEPLOYMENT PLAN is available. No realistic worst scenarios can be simulated.

In this context and within this limited study overview, it is not possible to determine a realistic margin to be used for radar. Results on margin to be taken into account are expected from other GALILEO project.
4.4 JTIDS/MIDS INTERFERENCE

The description of JTIDS/MIDS net is described in the appendix 2. In worst case, 128 slots of 444 pulses are emitted in one second over the 51 channels. Their power level and pulse spectrum have for consequences a blanking on all the useful bandwidth during the length of the pulses.

The pulse duration is 13µs maximum with a minimum of 2.5µs off time (-80dB rejection minimum): in the worst case, 10.5µs can be blanked. With a minimum of 50dB rejection between 1994MHz and 1197MHz, only 46 to 50 channels are disturbing to E5b.

The blanking duty cycle is thus given by the relation:

\[ Bdc = \frac{N_{\text{disturbing channels}} \cdot N_{\text{pulses/slot}} \cdot N_{\text{slot}} \cdot T_{\text{pulses/duration}}}{N_{\text{channels}}} \]

With \( N_{\text{channels}} \) number of authorised carrier frequencies, \( N_{\text{disturbing channels}} \) number of authorised carrier frequencies in the useful bandwidth, \( N_{\text{slot}} \) number of slots, \( N_{\text{pulses/slot}} \) number of pulses per slot, \( T_{\text{pulses/duration}} \) duration of one slot.

This induces a 6% blanking duty cycle and a 0.3dB degradation on the signal to noise ratio.

This result is compatible with [RD7] simulation results. The latter study (L5 case) from the MITRE conclude to a 0.9dB degradation on the signal to noise ratio considering the more numerous JTIDS/MIDS disturbing channels in the useful L5 band.

A 0.5dB margin is thus sufficient for JTIDS/MIDS interference.

Remark 1: The methodology is given on [RD12] to calculate the signal to noise degradation. For an in-band JTIDS/MIDS interference, it gives the following results for a blanking threshold equal to three times the variance of the thermal noise:

Remark 2: The JTIDS / MIDS deployment plan is confidential due to its military use. It is then not available.
4.5 CW INTERFERENCE

4.5.1 Introduction

The following systems generates harmonics in the GALILEO E5b and GPS L5 band:

- VHF communications systems
- TV emitters.

The following array presents the disturbing harmonics for GALILEO E5b:
Interference mitigation techniques for air receivers

Table 2: Disturbing CW harmonics for GALILEO E5b

<table>
<thead>
<tr>
<th>Type</th>
<th>Emission frequency</th>
<th>Disturbing harmonic</th>
<th>Power of the harmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHFCOM</td>
<td>[118MHz-137MHz]</td>
<td>9th harmonics</td>
<td>&lt;-46dBW (ARINC 716, 717 and 750)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[1062MHz-1233MHz]</td>
<td></td>
</tr>
<tr>
<td>VHFCOM</td>
<td>[118MHz-137MHz]</td>
<td>10th harmonics</td>
<td>&lt;-46dBW (ARINC 716, 717 and 750)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[1180MHz-1370MHz]</td>
<td></td>
</tr>
<tr>
<td>TV VHF 11</td>
<td>[198MHz-204MHz]</td>
<td>6th harmonics</td>
<td>TBC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[1188MHz-1224MHz]</td>
<td></td>
</tr>
<tr>
<td>TV channel 38</td>
<td>[204MHz-210MHz]</td>
<td>2nd harmonics</td>
<td>TBC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[1212MHz-1228MHz]</td>
<td></td>
</tr>
<tr>
<td>TV channel 7</td>
<td>[198MHz-206MHz]</td>
<td>6th harmonics</td>
<td>TBC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[1188MHz-1236MHz]</td>
<td></td>
</tr>
</tbody>
</table>

The following array presents the disturbing harmonics for GPS L5:

Table 3: Disturbing CW harmonics for GPS L5

<table>
<thead>
<tr>
<th>Type</th>
<th>Emission frequency</th>
<th>Disturbing harmonic</th>
<th>Power of the harmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHFCOM</td>
<td>[118MHz-137MHz]</td>
<td>9th harmonics</td>
<td>&lt;-46dBW (ARINC 716, 717 and 750)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[1062MHz-1233MHz]</td>
<td></td>
</tr>
<tr>
<td>VHFCOM</td>
<td>[118MHz-137MHz]</td>
<td>10th harmonics</td>
<td>&lt;-46dBW (ARINC 716, 717 and 750)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[1180MHz-1370MHz]</td>
<td></td>
</tr>
</tbody>
</table>

4.5.2 TV transmitter and ground-air VHFCOM

The free-space loss of a -46dBW-interference power is given by the following figure:

Table 4: Free-space degradation of a -46dBW-VHFCOM
For ground-air transmission VHFCOM and TV channel, the received power is negligible at 3000 feet and 40000 feet.

4.5.3 Air-ground VHFCOM

A special attention must be paid to VHFCOM air-ground transmission. Indeed, VHFCOM transmitter antenna and GNSS receiver antenna can be used on the same plane. To solve the problem, a trade-off must be made between:

- The high rejection of the VHFCOM harmonic
- Isolation between the antennas
- FDAF filtering when the disturbing channel is used (ultimate solution because 1MHz would be “blanked” during transmission and the transmission can be made during landing).

An air-ground emitter may emit a –46dBW harmonic. If we want to reject 10dB under the thermal noise (around –140dBW), an additional 94dB-rejection is needed.

50dB can be made by antenna isolation but a 44dB rejection filter have to be added to the VHFCOM emitter.
5 MITIGATION TECHNIQUES ENVISAGED FOR DME/TACAN

5.1 INTRODUCTION

Two types of solutions can be used in parallel: system solutions and signal processing solutions. System solutions are solutions that are taken into account in the definition of the system (signals, data rate, integrity message etc) and signal processing solutions are the one implemented in the receiver. Both types of solution have to be defined considering the other to find out the best compromise to cope with DME.

5.2 SYSTEM SOLUTIONS (ALREADY CHOSEN BY ICD)

5.2.1 DME frequencies reassignment

DME reassignment has been investigated as a potential solution. In the United States, re-assignment is only considered and not planned. In addition, no specific scenario is yet defined for L5-band.

Due to the already high-density assignment in the whole DME band in Europe, it proved to be impossible to reassigned DME beacons in plus or minus 9MHz near the E5b band.

Another point is DME removal beginning in 2010-2015 in France [RD9]. When DME beacons removal plan will begin in Europe, it will be interesting to remove the most disturbing beacons first.

This solution requires that all countries reassigned DME in the definite band.

5.2.2 E5 central frequency choice

ICD specifies the central frequency of E5b at 1207MHz for the safety of life service with integrity. The L5 frequency is at 1176MHz.
As we can see in the previous figure, the whole band is occupied. Nevertheless, a little hollow can be noticed between 1200-1205MHz. Due to the increasing aeronautical traffic, new DME/TACAN beacons are still planned to be installed. Beacons removing plan will start in 2010-2015. It is difficult to predict beacons assignment in the future. But today, E5b band contains less DME/TACAN frequency assignments than L5 and that was part of the choice.

However, radar’s frequency band is 1215-1400MHz. Out-of-band radar’s emissions are thus more significant for E5b than for L5.

5.2.3 Pilot/data channel

The concept of pilot/data channel is based on using two signals with the same carrier frequency: one is modulated by a PRN code without data (pilot) and the other by a PRN code and data.

The main advantages of using a channel without data are the following:
- Coherent integration time is possible as long as needed with all the advantages (no squaring loss).

The following figure illustrates the squaring loss:
A four-quadrant arctangent discriminator can be used for the Phase Lock Loop (period $2\pi$ instead of period $\pi$). We consider a cycle slip for a $2\pi$ slip instead of a $\pi$ slip. The cycle slipping is a phenomenon observed experimentally. Theoretical considerations offer no assistance to estimate at what signal to noise ratio and with which probability the various phenomena occurs (slipping of one cycle, slipping of several cycle, loop definitively out-of-lock). Moreover, the probability of the phenomenon is heightened with a low signal to noise ratio (presence of interference for example) and whether the input signal frequency is not equal to the VCO central frequency (dynamics of the plane for example). To provide data, simulations have been used modelling a practical loop to determine the cycle slip probability. As can be seen on the following figures, the cycle slip is less bound to occur for a pilot channel than for a data channel:

![Figure 11: Illustration of the squaring loss](image-url)
Figure 12: Cycle slip probability for a pilot channel

Figure 13: Cycle slip probability for a data channel
5.2.4 Useful bandwidth

Each DME/TACAN beacon emits on a 1MHz channel. The wider is the bandwidth the higher is the number of DME/TACAN beacons, which can interfere with the useful signal. A NB signal is thus less disturbed by DME than a WB signal. But the wider is the bandwidth, the more precise is the measure. A compromise must be made between precision and disturbance in the band.

This choice also depends of the chosen mitigation technique in the receiver (signal processing): elimination of the whole bandwidth of the interfered signal or elimination of the interfered frequencies only.

5.2.5 NB/WB

This solution was first envisaged but ICD does not include it anymore.

In Europe, a NB/WB solution was proposed in the definition of E5 signal in space as a way to cope with DME interference. In order to improve data demodulation for a lower signal to noise ratio, the data channel is proposed to be NB. The time occupation of DME interference is statistically ten times lower for NB than for WB. In case of blanking techniques, the signal to noise ratio losses in the loop due to DME interference would then be lower for NB than for WB.

An improved NB/WB solution would consist in weighting the contribution of NB and WB channels according to the noise level (including interference) on the WB channel. Such a solution would offer at least the following advantage: it would benefit from the NB channel robustness and from the WB channel accuracy when the interference level remains low. But a reassignment of the beacons emitting in the NB is essential to ensure continuity.

ICD did not envisage this solution anymore because a reassignment of the beacons in the 2MHz is not conceivable (agreement between countries).

5.2.6 Modulation type

The choice of modulation cannot be seen as a DME counter-measure. Only useful bandwidth is relevant. The modulation spectral shape is of secondary importance.

5.3 Signal processing solutions

5.3.1 Introduction

Signal processing solutions can be implemented in the receiver at different stages. These stages are represented on the figure here after.
The sooner an interference is treated the better the receiver works. First of all, DME can be treated with the antenna, like CRPA for example (I on the previous figure). We can then imagine the treatment in the RF part (II on the previous figure). The ADC dynamic naturally limits the power of strong pulse interference getting in the digital part (III on the previous figure). In the worst case, DME can be treated digitally (IV on the previous figure).

If DME are treated after the analogue-to-digital converter i.e. part IV, the RF architecture has to be dimensioned taking into account two significant points:

- ADC must have enough dynamic to code the pulses (the actual 3 bits ADC is not enough)
- RF architecture has to bring a non-distorted signal to the ADC i.e. a strong interference has to stay in the linear working part of amplifiers. That is to say that the RF architecture must have a large dynamic.
- Sample frequency has to be high enough not to alias powerful out-of-band interference in the useful band.

These three constraints increase the cost.

5.3.2 Currently envisaged solutions

5.3.2.1 Saturation of the ADC

ADC is used to convert from analogue to digital on a limited number of bits. An AGC is thus required for three reasons:

- Increased dynamic range: ADC can work correctly whatever the input power level
- Quantization level control: thermal noise is coded properly on the N-bits ADC
- Pulse interference suppression

The latter point is highly linked with the 1ms time constant (much higher than a pulse length, around 3.5µs). If a powerful pulse is received, AGC do not have time to react (diminution of the gain). ADC will thus code on the same level the analogue signal, which is over the quantification window. In other terms, the ADC will naturally cut pulses.

If the pulses have a high occupation rate, AGC can dramatically decrease the gain. At that time, availability is jeopardised. Indeed, the useful signal is not coded any more. A higher number of bits are thus needed to ensure a correct work.
5.3.2.2 Blanking

Pulse blanking is a simple technique to suppress pulsed interference by having the ADC output zeroes when a pulse is detected. A pulse is detected if its power is higher than a given threshold. Weak pulses may not be detected and will contribute to signal to noise losses.

The blanker dynamics implies a delay to return to its normal working state. This delay is commonly assumed to be approximately 1µs (See RD18). That is to say that after a blanking period the signal is kept zeroed during 1µs.

5.3.2.3 FDAF

This method uses the Fast Fourier Transform to determine frequencies corrupted by DME interference. The FFT algorithm performs a spectral analysis on the received signal. As the spectrum of the GALILEO E5 signal will be relatively flat across the whole frequency band, strong narrow band interference will be easily detectable.

From the spectral analysis, a filter pattern (with zeros and one) is determined, which allows the suppression of the frequency components including the useful signal components in the corrupted frequency bandwidth. To retrieve the signal, an inverse FFT is then applied on the filtered spectrum.

This solution is adapted to the DME/TACAN interference mitigation technique. Indeed, it can take into account DME/TACAN characteristics. It is not currently envisaged in receiver because of computation load and the current components’ technology. But in 2010-2015, this method can become competitive in terms of cost and performance.

5.3.3 Solutions based on other concept

5.3.3.1 Adaptive antennas

Adaptive antenna processing cannot be use for DME treatment. Indeed, this method consists in adapting the antenna gain according to the direction of the jammer with a definite refreshment time. The refreshment time has to be the shortest possible taking into account technology, consumption and price. Today adaptive antennas have a too long refreshment time compared to a DME time length. In 10-15 years, the concept will be feasible but the consumption will stay significant. Moreover, the number of interference treated depends on the complexity of the adaptive antenna and at high altitude, the number of beacons in view is quite significant: only few interference would be treated. This mitigation technique is more adapted for strong intentional jammer in the band.
5.4 COMPARISON BETWEEN INTERFERENCE MITIGATION TECHNIQUES SOLUTIONS

5.4.1 Introduction
In the previous paragraph, two types of solutions were described: system solutions and signal processing solutions. Both types of solution can be used in parallel. The aim of the paragraph is to compare and to combine solutions to determine the better compromise to cope with DME interference.

5.4.2 Comparison between solutions
## Interference mitigation techniques for air receivers

### Table 5: Comparison between solutions

<table>
<thead>
<tr>
<th>Solutions</th>
<th>Feasibility</th>
<th>Performance</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System solutions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DME reassignment</td>
<td>VERY UNLIKELY (agreements between countries)</td>
<td>Excellent</td>
<td>EXPENSIVE</td>
</tr>
<tr>
<td>Partial DME reassignment</td>
<td>UNLIKELY (agreements between countries)</td>
<td>Excellent for NB use but not essential</td>
<td>Not so expensive to put in practice</td>
</tr>
<tr>
<td>E5 frequency central choice</td>
<td>Chosen (1207.045MHz)</td>
<td>Average influence</td>
<td>None</td>
</tr>
<tr>
<td>Pilot/data channel</td>
<td>Chosen</td>
<td>Great influence</td>
<td>Low-cost</td>
</tr>
<tr>
<td>NB/WB</td>
<td>Rejected (no partial DME reassignment)</td>
<td>Great influence and lower or greater than WB/WB depending on the signal processing solutions</td>
<td>Low-cost</td>
</tr>
<tr>
<td>Bandwidth 2MHz</td>
<td>Rejected (same as below)</td>
<td>Depend on the signal processing solutions</td>
<td>Low-cost</td>
</tr>
<tr>
<td>Bandwidth 10MHz</td>
<td>Rejected (less accurate than a 20MHz bandwidth)</td>
<td>Depend on the signal processing solutions</td>
<td>Low-cost</td>
</tr>
<tr>
<td>Bandwidth 20MHz</td>
<td>Chosen (accuracy)</td>
<td>Depend on the signal processing solutions</td>
<td>Low-cost</td>
</tr>
<tr>
<td>Bandwidth 30MHz</td>
<td>Rejected (complexity of the signal processing in the receiver)</td>
<td>Depend on the signal processing solutions</td>
<td>High cost for receiver</td>
</tr>
<tr>
<td>Modulation choice</td>
<td>Chosen (BPSK)</td>
<td>NO INFLUENCE</td>
<td>Low-cost</td>
</tr>
<tr>
<td><strong>Signal processing solutions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturation of the ADC (number of bits needed)</td>
<td>Choice to do (Implicitly implemented)</td>
<td>Good influence</td>
<td>Low-cost</td>
</tr>
<tr>
<td>Blanking</td>
<td>Easy</td>
<td>Good influence</td>
<td>Low-cost</td>
</tr>
<tr>
<td>FDAF</td>
<td>Possible in 10-15 years</td>
<td>Excellent</td>
<td>To be assessed for future receivers</td>
</tr>
<tr>
<td>Adaptative antennas</td>
<td>Possible</td>
<td>Excellent for intentional jamming</td>
<td>To be assessed for future receiver</td>
</tr>
<tr>
<td>Time-frequency solutions</td>
<td>Possible in 10-15 years</td>
<td>Excellent</td>
<td>To be assessed for future receivers</td>
</tr>
</tbody>
</table>

### 5.4.3 Combinations of solutions

Several combinations (system solutions and signal processing solutions) can be chosen depending on the cost and performance requested. The following table presents several combinations of solutions:
Conceivable combinations

<table>
<thead>
<tr>
<th>System solutions (Chosen)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DME reassignment</td>
</tr>
<tr>
<td>Partial DME reassignment</td>
</tr>
<tr>
<td>E5 frequency central choice</td>
</tr>
<tr>
<td>Pilot/data channel</td>
</tr>
<tr>
<td>NB/WB</td>
</tr>
<tr>
<td>Bandwidth 2MHz for data</td>
</tr>
<tr>
<td>Bandwidth 10MHz for data</td>
</tr>
<tr>
<td>Bandwidth 20MHz for pilot</td>
</tr>
<tr>
<td>Bandwidth 20MHz for data</td>
</tr>
<tr>
<td>Modulation choice</td>
</tr>
</tbody>
</table>

Signal processing solutions (To choose to develop a receiver)

<table>
<thead>
<tr>
<th>Reason of combination choice</th>
<th>Cheap Low data rate*</th>
<th>Cheap Low data rate*</th>
<th>Complex Efficient</th>
<th>Complex Efficient</th>
<th>Complex Efficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation of the ADC</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>Blanking</td>
<td>×</td>
<td>O</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>FDAF</td>
<td>×</td>
<td>×</td>
<td>O</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Adaptive antennas</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>O</td>
<td>×</td>
</tr>
<tr>
<td>Time-frequency solutions</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>O</td>
</tr>
</tbody>
</table>

○ Chosen option, × Not used, ⊗ Negative influence

Table 6: Conceivable combination of solutions

* “Low data rate” means that data rate shall be lower than 200BPS/400SPS if a Viterbi decoding technique is used.

Through the table, we can observe that for the chosen system solution, several signal processing solution can be used: blanking, FDAF, adaptive antennas etc. Depending on the price and the requirement of the category of the plane, a signal processing solution, i.e. mitigation technique, would be chosen.
INTERFERENCE MITIGATION REQUIREMENTS

6.1 CURRENT REQUIREMENTS IN EXISTING STANDARD

6.1.1 Current requirements in existing standard

Standards for continuous and pulsed interference are considered independently.

For continuous interference, a maximum equivalent white noise interference after correlation is defined. On the [AD1] (L1 receivers, GPS only), two types of requirements were defined for continuous interference. A first test is based on CW interference. A receiver should cope with a minimum CW interference power level for several carrier frequencies. A second test is based on narrow band interference.

[AD1] (L1 receivers, GPS only) proposes two types of requirements for pulsed interference. These requirements are based on pulsed interference scenarios. One scenario is composed of in-band pulsed interference and the other composed of out-of-band pulsed interference.

[RD18] proposed another requirements for DME/TACAN interference. It consists of determining a maximum tolerable interference level in dBW/MHz. The maximum is around –110dBW/MHz for track mode and around –106dBW/MHz for acquisition mode. This method does not take into account pulse duty cycle and pulse widths. Indeed, if a pulse blanking is implemented with a –116.5dBW threshold ([RD3]) and the pulse duty cycle is high, a receiver will not work correctly. This approach is not complete enough for non-stationary interference.

A test of pulsed interference scenarios is thus needed to really cover an adapted requirement for E5b/L5 interference mitigation standardisation.

6.1.2 Current pulsed test definition

On [AD1] (L1 receivers, GPS only), a receiver should work correctly with the following in-band and near-band pulse interference scenario:

<table>
<thead>
<tr>
<th>GPS only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power</td>
</tr>
<tr>
<td>Pulse width</td>
</tr>
<tr>
<td>Pulse duty cycle</td>
</tr>
</tbody>
</table>

Table 7: In-band and near-band pulse interference scenario tests in [AD1]

Considering pulsed interference in L1 band, this scenario is acceptable. To make a standard in E5b/L5 band, another scenario should be found and surely a more complex one.

The proposed test for E5b/L5 band is given in 6.2.4.
6.2 REQUIREMENTS FOR RECEIVER USING GALILEO E5B OR GPS L5 FREQUENCY BAND

6.2.1 Methodology

5.1.1 points out that a test composed of pulsed interference scenarios is needed for test standardisation. First a standard pulsed interference environment should be determined (worst case in Europe). Then, criteria should be listed. Finally a test procedure for certification should be described.

6.2.2 Definition of a standard environment

One or several scenarios should be chosen in order to represent a worst case in practice over Europe, the United States and Japan. These scenarios should take into account DME installations and removals in the next years.

A database [AD5] gives the current characteristics of DME beacons over Europe. However, the number of DME today is not necessarily representative since some more DME in Europe might be added in the coming years to cover classical navigation needs. However DME installations are limited by frequency allocations. Furthermore, other systems like GPS, GALILEO, ILS will replace this system and DME installation should thus slow down (see [RD9]).

In 2010, we can make three hypotheses:
- The number of TACAN beacons might level off.
- The number of DME beacons might be increased by 20% (worst case).
- Probability for a DME/TACAN beacon to have a given emission frequency may the same all along E5 band.

In our worse case over Europe developed in paragraph 3, around 18 DME/TACAN beacons are in view emitting between 1197MHz and 1215MHz and 29 between 1166MHz and 1186MHz. With 20% more DME beacons in the worst case in 2010, we would have around 22 DME/TACAN beacons emitting between 1197MHz and 1215MHz and 35 between 1166MHz and 1186MHz.

It is proposed to test receivers in such configuration. But it is highly probable that from the 2020 decade, DME beacons will decrease. However, for the 2010-2020 decade, a conservative and worst case scenario is needed.

Remark: We suppose that the interference rejection before 1197MHz is sufficient to cause acceptable C/N0 losses (See chapter §5.3).

We remark that receivers have to be protected against damage due to high-powered pulses even if a low altitude DME scenario is not made.

6.2.3 Criteria

6.2.3.1 Robustness criteria

6.2.3.1.1 Measure

Robustness of the phase and code loops can be observed through the signal to noise ratio after correlation. The signal to noise ratio has to be greater than the tracking and acquisition thresholds to ensure robustness.
The goal of the next paragraph is to determine the threshold to compare to the signal to noise ratio after correlation.

6.2.3.1.2 Value to ensure possible phase tracking

6.2.3.1.2.1 Introduction
Two factors have to be taken into account when establishing the tracking threshold value:

- Cycle slip probability: cycle slipping is observed experimentally. The phase detector characteristic is $2\pi$ periodic. From time to time, the loop jumps from one stable operating point to another similar $k2\pi$ further on (slip of $k$ cycle). The various phenomena is: slipping of one cycle, slipping of several cycles, loop definitively out of lock. Theoretical considerations offer no assistance in this domain.
- Data demodulation: it is essential to demodulate integrity data with a very low BER to warranty integrity availability on a time scale compatible with air navigation operation.

6.2.3.1.2.2 Cycle slips
The aim of this section is to determine the signal to noise ratio for which the cycle slip probability is negligible.

Simulations are launched on the principle of Monte-Carlo statistics to ensure the results repeatability. Hypotheses are:

- A WB/WB pilot/data signal,
- the code and carrier loops are made on the pilot channel only,
- all the energy is on the pilot channel (conclusion takes into account this hypothesis).

Ten simulations of hundred seconds are tested for different signal to noise ratio. We plot the time to loose lock and the cycle slip probability on the figure below.
Figure 15: Time to loose lock versus signal to noise ratio on the pilot channel

We can consider that a signal to noise ratio superior to 20dBHz let the simulated loops work correctly. This observation is not enough to ensure a correct work for a longer time. We thus plot the cycle slip probability.
The cycle slip probability is negligible ($<10^{-5}$) when the signal to noise ratio is higher than 22dBiHz.

The pursuit threshold is thus:

$$22\text{dBiHz} + 3\text{dB} + 3\text{dB} = 28\text{dBiHz}$$

We thus consider that the C/N0 phase tracking threshold is 28dBiHz.

6.2.3.1.2.3  Data demodulation
The aim of this paragraph is to determine the signal to noise ratio for which the bit error probability is negligible.

We suppose that data are encoded at ½ rate on 7 bits and the decoding technique used is a Viterbi algorithm. The next figure shows the relative performance of Viterbi.

![Graph showing theoretical performance of convolutional code](image)

**Figure 17: Theoretical performance of convolutional code**

\[ \varepsilon_b/N_0 = C/N_0 - 10\log(D_r) \]
\[ \varepsilon_b/N_0 \]: Energy per bit (dB)
\[ C/N_0 \]: Signal to noise ratio (dB.Hz)
\[ D_r \]: Data-rate (Hz)

We note that data rate has a great influence on integrity. The following figure gives the signal to noise ratio demanded to have a bit error probability rate of $10^{-6}$ with the following hypotheses:

- Data encoded at ½ rate on 7 bits and the decoding technique used is a Viterbi algorithm
- Signal power equally divided between a pilot channel and a data channel (3dB)
Figure 18: Signal to noise ratio demanded for BER=$10^{-6}$ versus data rate with a Viterbi decoding technique

For a data rate of 125 BPS (250 SPS) and a soft decision algorithm, the signal to noise ratio required is 29dBHz.

NB: Choice of the data on the signal is significant to determine the value to ensure. For example on L5 signal, the data rate is equal to 50 BPS (100 SPS). The signal to noise ratio demanded is 25dBHz for a soft decision algorithm.

6.2.3.1.3 Value to ensure possible acquisition

6.2.3.1.3.1 Introduction

From a theoretical point of view, the acquisition threshold could be at the extreme as low as the tracking threshold. Actually this is not the case since it would need unrealistic receiver complexity or too long acquisition time.
The real issue is to achieve such an acquisition within an operational time and with reasonable hardware complexity, which implies higher minimum C/N0 value than for the tracking threshold. In the civil aviation domain a few minutes for acquisition time are commonly accepted.

The short analysis presented below aims at introducing typical C/N0 which may be considered in acquisition phase when using E5b.

6.2.3.1.3.2 Main issues for acquisition

- Initial Time uncertainty
  The 1mn time precision may only be used in the process of selection of initial set of satellites (when used jointly with available initial position). Such uncertainty implies that a whole search on the 10230 chip of the code length has to be used. The search process used in this analysis is a dwell method, with a ½ chip progression, and a coherent integration time of 1ms. Pilot and Data channel are both used.

- Initial Position uncertainty
  The 60 NM initial position may be used for first set of satellite selection.

- Initial Doppler uncertainty
  Residual Doppler associated to uncertainty on relative satellite vehicle velocity may be resolved using on board primary speed source (Air speed) and satellite available information (through initial position, time and almanac). Residual Doppler from clock drift at power on may be reduced by calibration and storage at each power on.
  In such condition residual Doppler lower than 50m/s (250Hz) may be considered. This is consistent with the 1ms coherent integration time used in the search process and with one unique Doppler cell.
  It may also be mentioned that other means to manage the residual Doppler may be considered such as for example using FFT analysis of the correlation.

- Number of correlators
  Basically per satellite channel (assuming pilot and data with two different codes) 4 correlators are at least needed in tracking (punctual and early-late for pilot and for data channel). These correlators may also be used in acquisition phase, which is the assumption of this analysis.
  It is needed to point out that the acquisition time is directly linked to the number of correlators used. Consequently in case more performances are required on the acquisition time, an increased number of correlators per channel may be a solution. The impact on receiver’s complexity may be still acceptable for future receivers.

- Satellites acquisition strategy / Number of channels available
  Different strategy may be envisaged to select and acquire a first set of Satellites for first fix.
  When the position uncertainty is low compared to code length and (to the time uncertainty) the common strategy is to focus acquisition on the stronger satellite signal, to resolve the time, and then to quickly acquire the other satellites.
  In the considered configuration this is not the case and a strategy consisting in first focusing the acquisition on the four more favourable satellites, demodulating the ephemeris, resolving the position, velocity and time, and then acquiring the remaining satellites may be more efficient.
  The strategy is also closely linked to the number of available channels. For future GNSS receiver, which will be Multi, frequencies and Multi constellation the typical number of channels should typically be at least 60 (15 for each all in view constellation, two frequencies, two constellations). During acquisition more channels may be dedicated than in tracking phase. For example if GPS L1, Galileo L1 and GPS L5 channel are not used (due to interference for instance) all resources may be dedicated to E5b, which means at least four time more
correlators (in the other case a PVT solution based either GPS L1, Galileo L1 or GPS L5 or is likely to enable quick acquisition).

- Acquisition time defined at 90%
  This impacts directly the tuning of PMD (probability of missed detection) and PFA (probability of false alarm) of code search process and consequently integration and acquisition time.
  In this analysis the process has been tuned for PMD 2.5% and PFA 1% (Total PFA for the search of 2*10230 cells) as example. Different other strategy may be considered.

- Clock stabilisation time
  Depending on type of clock the acquisition time budget should include some extra time. Progress in OCXO technology is such that 10 seconds warm up time are only needed.

- Acquisition of satellites data
  GALILEO corresponding messages and time to acquire it are still on consolidation. Typically a TBD has to be considered.

- Lock on secondary correlation lobes
  This issue is a dimensioning one when using short length code (1023), is not so much important when using the 10,230 E5b code length.

6.2.3.1.3.3 Typical acquisition time and C/N0
The curves in the next page represent the acquisition time versus the signal to noise ratio for following configuration:
- E5b only signal used
- Initial position uncertainty within 60 NM and time uncertainty within 1 minute
- 4 satellites searched
- Pilot and data channel in parallel
- 30 complex correlators on each satellite (60 channels x 2 complex correlators / 4 satellites)
- PND = 2.5% on each satellite
- Probability of Detection = 90% (first dwell) for all 4 satellites (this is the mean value of the search time, assuming a 0.9 probability of detection)
- PFA = 1% (total PFA for the search of 2*10230 cells)
- Single dwell method, ½ chip spacing

Figure 19: Acquisition time versus the signal to noise ratio (90% PD) plots the maximum search time at 90% (more optimised search chip strategy may be envisaged) versus the $C/N_0$. The parameter used is the signal to noise ratio for the composite signal (both pilot and data E5b signal). This is pointed out here so that to avoid misinterpretations when comparing with other results which might be expressed using a $C/N_0$ per channel.

The integration time (total cells energy integration to achieve a good acquisition) is directly linked to the acquisition time. The poorer the expected $C/N_0$, then the longer the integration time must be, in order to have success of signal acquisition. For a given cells length, if the $C/N_0$ decreases, the number of non-coherent integrations may increase.

1 Prospect is that future receivers will typically offer 120 complex correlators. Such figure is consistent with multi-constellation, multi-frequency receiver: 15*2 complex correlators for pilot and data channel, for 2 frequencies, for 2 constellations.
To derive the acquisition time from the search time given on Figure 19 (assuming a 90% probability of detection), two corrections have to be included. Effect of correlation losses and extra time related at least to the clock warm up time or to the satellites data acquisition time.

The required C/N0 in the figure has to be increased as indicated below due to misalignment losses:

- Residual Doppler: 0.9 dB (250 Hz residual Doppler)
- 1/2 chip search process: 0.6 dB

Total alignment losses: 1.5 dB

Extra time:
It is assumed that the GALILEO E5b data are defined so that the acquisition of data needed for the first fix might be possible in less than 20 s. Taking into account every miscellaneous times (clock warm up, synchrob, data acquisition) a 30 sec extra time may be considered.

6.2.3.1.3.4 Typical figures

Figure 19: Acquisition time versus the signal to noise ratio (90% PD) let us give the following array of typical figures:

<table>
<thead>
<tr>
<th>C/N0 (dB)</th>
<th>C/N0 + losses (dB)</th>
<th>Max acquisition time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>29.5</td>
<td>31 + 30</td>
</tr>
<tr>
<td>34</td>
<td>32.5</td>
<td>15 + 30</td>
</tr>
<tr>
<td>35</td>
<td>33.5</td>
<td>10 + 30</td>
</tr>
</tbody>
</table>

Table 8: Acquisition time for given signal to noise ratio
6.2.3.2 Precision criteria

6.2.3.2.1 Measure

As the position of the antenna is known, noise on the position can be determined. In the mark longitude-latitude-altitude, measurements let us know:

- $\sigma^2_{\text{latitude}}$
- $\sigma^2_{\text{longitude}}$
- $\sigma^2_{\text{altitude}}$

But this noise depends on the geometry of the satellites. To find an independent criterion, we have to deduce pseudo-distances from these measures. For that, a receiver gives us $H_{dop}$ and $V_{dop}$.

We deduce the noise on the pseudo-distance with:

$$\sigma^2_{\text{pseudodistance}} \simeq \left( \frac{\sigma^2_{\text{latitude}} + \sigma^2_{\text{longitude}}}{2} \right) \approx \frac{\sigma^2_{\text{altitude}}}{V^2_{dop}}.$$

6.2.3.2.2 Value to ensure

Value to ensure is phase of flight dependent.

6.2.4 Proposed test definition for E5b/L5 band

A receiver should work ensure robustness and precision criteria with interference scenarios whose characteristics are the following:

- 27 DME/TACAN beacons emitting between 1197MHz and 1215MHz
- 35 DME/TACAN beacons emitting between 1166MHz and 1186MHz
- Power of each beacon chosen at random between $-100\text{dBW}$ and $-125\text{dBW}$ (Justification available in Figure 6)

This test is representative of a flight at 40000 feet. It should be repeated several times.

Remark: Another test should confirm that receivers are protected against damage due to high-powered pulses.

6.3 Requirements for multimode receiver

6.3.1 Introduction

Civil aviation demands separate interference mode of failure on E5b and L5 frequency bands. An interference, which affects E5b band must not disturb L5 frequency bandwidth and vice versa.

The strongest non-intentional interference that can be identified on L5 should thus be attenuated by the E5b out-of-band filter to have a post-attenuation power at least 10dB lower than the thermal noise in order to make the residual interference negligible.
6.3.2 *Strongest received interference*

The following figures show the maximum interference power after the receiver antenna:

![Figure 20: Interference peak power after the receiver antenna for beacons seen on the HORIZON (10°-elevation angle)](image1)

![Figure 21: Interference peak power after the antenna for beacons seen on the VERTICAL](image2)
The hypotheses are the following:

- Peak power: 31/42dBW peak power for DME/TACAN respectively, 30dBW for JTIDS/MIDS (power emitted from the beacon)
- Antenna gain of the receiver: -10dB on the horizon, -20dB on the vertical
- Antenna gain of the emitter: 0dB for JTIDS and the following antenna diagram for DME/TACAN.

![Diagram antenna for DME/TACAN emission](image)

The worst case is the 10°-elevation angle scenario. At 3000 feet, -70dBW peak power after receiver antenna can potentially be received at the input of the receiver. At 12km, this level comes down to -85dBW.

### 6.3.3 Technical solutions

In the worst case (at 3000 feet), we may receive a –70dBW TACAN interference and the noise level has a power of –127dBW (-204dBWHz with a 4dB noise factor and 20MHz bandwidth). A 70dB rejection ensures that a –70dBW interference will be attenuated more than 10dB under the noise floor level.

Here are the possible solutions to ensure that an interference on E5b will not disturb E5a and vice-versa:

- Either a 70dB rejection is made between E5b and L5. This can be possible with two separated HF part of the receiver, but probably not cost effective
- Either some XXdB (cost-effective, lower than 70dB) rejection is made between E5b and L5 using 2 separated HF. This implies that, from time to time, some out of useful bandwidth high power interference are not completely deleted and are aliased into the useful bandwidth by ADC. Then the blanker or the FDAF implemented behind will delete it with nearly no impact on robustness (there is anyway little interference received at the same location with a high power).
- Or using a unique HF part with a wider bandwidth (E5-L5): in that case, a common powerful interference blanking is implemented before coding. Then a digital separation between L5 and E5b is digitally performed, using on each final digital channel a mitigation process (either blanking or FDAF) to cancel remaining interference. In this case, ADC coding range will limit the rejection.

The two latest hypotheses are represented on the following figures:
Figure 23: Architecture synopsis: isolation between E5b and L5 made with digital filters (See [RD20])
6.3.4 Isolation required between E5b and L5

In the previous section, we saw two options to implement isolation between E5b and L5. The architecture with analogue isolation requires a trade-off between aliased interference in the band and the rejection that is accessible. The architecture with digital isolation requires a trade-off between the blanking duty cycle of the out-of-band pulses and the rejection that is accessible. In fact, trade-offs are of the same complexity in both cases: only the technology will decide.

The trade-offs for the latter point are the following:
Digital isolation architecture: –80dBW blanking threshold and 60dB-digital rejection (C/N0 losses due to blanking)
Analogue isolation architecture: 60dB-analogue rejection (C/N0 losses due to –60dBW interference minus 60dB-rejection aliased in the band).

Digital isolation architecture: –90dBW blanking threshold and 50dB-digital rejection (C/N0 losses due to blanking)
Analogue isolation architecture: 50dB-analogue rejection (C/N0 losses due to –60dBW interference minus 50dB-rejection aliased in the band).

Digital isolation architecture: –100dBW blanking threshold and 40dB-digital rejection (C/N0 losses due to blanking)
Analogue isolation architecture: 60dB-analogue rejection (C/N0 losses due to –60dBW interference minus 40dB-rejection aliased in the band).

A calculation has been made to counter the maximum number of powerful beacons in view for different position of a plane over Europe (0.1° step in latitude and longitude from 10W-35E, 35N-75N between [1164MHz-1215MHz]). Considering simulations being run for 2700 pps and 3600 pps DMEs and TACANs pulsed interference, the results are the following:

<table>
<thead>
<tr>
<th>Peak power superior to</th>
<th>Maximum beacons in view at 1km - 3000 feet</th>
<th>Maximum beacons in view at 12km - 40000 feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>– 80dBW</td>
<td>0 (no position of plane found but possible – refinement better than 0.1° step)</td>
<td>0 (no position of plane found but possible – refinement better than 0.1° step)</td>
</tr>
<tr>
<td>– 90dBW</td>
<td>2</td>
<td>0 (no position of plane found but possible – refinement better than 0.1° step)</td>
</tr>
<tr>
<td>– 100dBW</td>
<td>8</td>
<td>4 (no position of plane found but possible – refinement better than 0.1° step)</td>
</tr>
<tr>
<td>– 110dBW</td>
<td>15</td>
<td>18</td>
</tr>
</tbody>
</table>

Considering 3600pps with a 10µs length (worst case) and given coarse blanking levels, the maximum degradation on the signal to noise ratio is given on the following table 10. This table synthesizes the maximum C/N0 degradation according to the number of beacons in view on E5A+E5B band, as described in Table 9.

The simulation results are given, assuming that, after a given isolation between L5 and E5B, the in-band DME/TACAN impact is only due to coarse blanking levels.
Table 10: Maximum C/N0 degradation due to a coarse blanking of powerful pulses

<table>
<thead>
<tr>
<th>Blanking of peak power superior to</th>
<th>Maximum C/N0 degradation at 1km - 3000 feet</th>
<th>Maximum C/N0 degradation at 12km - 40000 feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>-80dBW</td>
<td>0dB</td>
<td>0dB</td>
</tr>
<tr>
<td>-90dBW</td>
<td>-0.3dB</td>
<td>0dB</td>
</tr>
<tr>
<td>-100dBW</td>
<td>-1.5dB</td>
<td>-0.7dB</td>
</tr>
<tr>
<td>-110dBW</td>
<td>-3.4dB</td>
<td>-4.5dB</td>
</tr>
</tbody>
</table>

The table 10 synthesizes the maximum C/N0 degradation according to the number of beacons in view on E5_A and E5_B bands, as described in table 9.

6.3.5 Conclusion

0.3dB is an acceptable degradation. A coarse blanking can thus be made on the pulse with a power higher than -90dBW and a 50dB rejection between L5 and E5b can be thus sufficient to ensure isolation.

Thus, an acceptable standard interference rejection specification for pulsed interference could be expressed as follows when dealing with civil aviation receivers:

![Figure 25: Standard interference rejection specification](image-url)
7 EFFICIENT INTERFERENCE MITIGATION TECHNIQUE SOLUTIONS IN ACCORDANCE WITH REQUIREMENTS

7.1 INTRODUCTION

With the current ICD definition (chosen system solutions), two cost-effective methods can be envisaged from a receiver point of view to cope with this non-intentional interference: blanking and FDAF.

The mitigation technique performance results are taken from Task F simulations results [RD14]. The simulations have been running for different hypotheses of HF filters. Hypotheses of signal are taken from the SIS ICD [RD15].

7.2 LINK BUDGET

The aim of the paragraph is to determine the minimum signal to noise ratio with which a receiver should work with, in a worst case.

<table>
<thead>
<tr>
<th>Theoretical C/N0 available (dBHz, made of)</th>
<th>Value (dBHz)</th>
<th>Margin (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Power (dBW)</td>
<td>-155</td>
<td>0</td>
</tr>
<tr>
<td>Antenna Gain (dBi)</td>
<td>-4.5</td>
<td>+1.5</td>
</tr>
<tr>
<td>Thermal Noise level (dBW/Hz)</td>
<td>-204</td>
<td>0</td>
</tr>
<tr>
<td>Receiver noise figure (dB)</td>
<td>4</td>
<td>+1</td>
</tr>
<tr>
<td>N0 (dBW/Hz)</td>
<td>-200</td>
<td>+1.5</td>
</tr>
<tr>
<td>Receiver Implementation losses (dB)</td>
<td>-2</td>
<td>0</td>
</tr>
<tr>
<td>Implementations losses (dB)</td>
<td>38.5</td>
<td>+4</td>
</tr>
</tbody>
</table>

Table 11: Link budget

The implementation losses of 2 dB include IF filtering loss, ADC losses, and space vehicle imperfection.

The minimum signal to noise ratio is thus 38.5dBHz without interference degradation.

2 A margin can be taken because some degradation figures are taken from ARINC 743A and we consider these values as pessimistic.

3 A margin can be taken, assuming a N0 power of –201.5 dBW/Hz rather than –200 dBW/Hz, initially used.
7.3 SIMULATIONS HYPOTHESES

7.3.1 E5-signals hypotheses
According to the [RD 14] study, the analysis is focused on E5 architecture details:

- L5 signal: It is centred at 1176.45 MHz and modulated by a BPSK (10). The limits of the ARNS band are 960 MHz and 1215 MHz. Thus, no constraints of filtering exist for this band.
- E5B signal: We use the hypothesis on an E5 B carrier frequency at 1207 MHz and modulated by a BPSK (10). The Front-End (i.e. the resulting filter due to RF and digital input filtering) has to protect:
  - Over 1215 MHz frequency band with a 70dB isolation
  - Below 1197 MHz frequency band with a 50dB isolation

7.3.2 Methodology used for simulations
The methodology is available in Appendix 1.

7.4 MITIGATION TECHNIQUES PERFORMANCES FOR DME/TACAN INTERFERENCE

7.4.1 Robustness or signal to noise ratio with treatment of DME/TACAN interference

The following array gives the minimum accessible C/N0 with treatment of DME/TACAN interference:

<table>
<thead>
<tr>
<th></th>
<th>Blanking</th>
<th>FDAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>HYP1</td>
<td>33.9dBHz</td>
<td>35.7dBHz</td>
</tr>
<tr>
<td>10Mcps-code chipping rate</td>
<td>Fr</td>
<td></td>
</tr>
<tr>
<td>Front-end-filter characteristics:</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>Central frequency: 1207MHz</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Bandwidth: 8MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HYP2</td>
<td>33.1dBHz</td>
<td>35.3dBHz</td>
</tr>
<tr>
<td>10Mcps-code chipping rate</td>
<td>Fr</td>
<td></td>
</tr>
<tr>
<td>Front-end-filter characteristics:</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>Central frequency: 1204MHz</td>
<td>M</td>
<td></td>
</tr>
<tr>
<td>Bandwidth: 16MHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 12: Minimum accessible C/N0 considering dimensioning scenario (high altitude), only DME/TACAN interference have been considered

7.4.2 Accuracy

7.4.2.1 Introduction
Accuracy results presented here are only the receiver measurement accuracy. This does not imply conclusion on the integrity, continuity, availability and time to alert of the service.

The total budget shall include system contribution such as:

- Ephemeris data accuracy
- Satellite clock accuracy
• Ionosphere error
• Troposphere error
• Multipath error

This is not the scope of our study. However, it would be interesting to make a link budget of available accuracy.

7.4.2.2 Accuracy of the receiver measurement or standard deviation on code measure

The following tables present standard deviation on the code measure:

<table>
<thead>
<tr>
<th>HYP1</th>
<th>Blanking</th>
<th>FDAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>10Mcps-code chipping rate</td>
<td>0.61m</td>
<td>0.61m</td>
</tr>
<tr>
<td>Front-end-filter characteristics:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central frequency: 1207MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth: 8MHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HYP2</th>
<th>Blanking</th>
<th>FDAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>10Mcps-code chipping rate</td>
<td>0.75m</td>
<td>0.54m</td>
</tr>
<tr>
<td>Front-end-filter characteristics:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central frequency: 1204MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth: 16MHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 13: Accessible accuracy for a high altitude scenario (40000 feet) with a 1Hz-code loop filter bandwidth, only DME/TACAN interference have been considered

<table>
<thead>
<tr>
<th>HYP1</th>
<th>Blanking</th>
<th>FDAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>10Mcps-code chipping rate</td>
<td>0.60m</td>
<td>0.52m</td>
</tr>
<tr>
<td>Front-end-filter characteristics:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central frequency: 1207MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth: 8MHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HYP2</th>
<th>Blanking</th>
<th>FDAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>10Mcps-code chipping rate</td>
<td>0.46m</td>
<td>0.48m</td>
</tr>
<tr>
<td>Front-end-filter characteristics:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central frequency: 1204MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth: 16MHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 14: Accessible accuracy for a low altitude scenario (3000 feet) with a 1Hz-code loop filter bandwidth, only DME/TACAN interference have been considered
8 IMPACT OF THE MITIGATION TECHNIQUE ON RECEIVER COST/COMPLEXITY

8.1 INTRODUCTION

Only the two cost-effective methods from a receiver point of view are presented hereafter.

8.2 BLANKING TECHNIQUE

8.2.1 Chosen implementation of blanking

If an AGC is used in the receiver, an estimation of power is already implemented. To avoid redundancy, this estimation of power can be used for the blanking technique. Moreover, it is important to avoid AGC variation due to very strong repeated pulses: to work correctly, the power estimation should be implemented after blanking to prevent the use of corrupted sample.

The following figure shows a synopsis of the chosen implementation:

![Figure 26: Implementation of blanking in a receiver](image)

8.2.2 Cost

The blanking technique as described in the baseline implementation has a very little impact on the complexity of the receiver and even less impact if it fits in the AGC loop.

8.3 FDAF TECHNIQUE

8.3.1 Chosen implementation

8.3.1.1 Introduction

FDAF technique will be implemented in digital. It requires a good accuracy in the encoding of the digital signal (10-12 bits ADC). It can be implemented either with a DSP or with an ASIC. The computation has to be done in real time with the following complexity (N number of point treated in the same time):
8.3.1.2 Use of a DSP
This processor would have high consumption and would probably be expensive even in ten years time.

8.3.1.3 Use of cabled logic
The use of cabled logic is possible. A FPGA can be developed for the four steps of the FDAF technique. This technique is quick enough.

8.3.2 Cost
For the present, the additional cost to implement this technique, as described here before, is likely to be tremendous compared to the basic blanking. It needs a complete new design of the receiver at the front-end level (high linearity of the analogue part + 10-12 bits ADC). If the design of the front-end level is already done for another reason (adaptive antenna for example), the additional cost of FDAF is only due to the computation load for DSP implementation and the additional component/consumption for a FPGA implementation. Nevertheless the evolution of FPGA and DSP cost until 2008 is difficult to establish.

8.4 SYNTHESIS ON ADDITIONAL COST/COMPLEXITY OF MITIGATION TECHNIQUE
This paragraph has been developed in [RD14].

We suppose that the price of the receiver without blanking is $P_{\text{ini}}=100$. This receiver has a high dynamic capability: ADC with a 10-12 bits, linearity of HF components. Moreover, we suppose that it has no AGC, following the current tendency.

The following array gives the estimated price today and in 2010’s:

<table>
<thead>
<tr>
<th>Estimated price</th>
<th>Non Protected</th>
<th>With Blanking</th>
<th>With FDAF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Today</strong></td>
<td>$P_{\text{ini}}$</td>
<td>$P_{\text{ini}} + P_{\text{bl}}$</td>
<td>$P_{\text{ini}} + 20 \cdot P_{\text{bl}}$</td>
</tr>
<tr>
<td><strong>in the 2010’s</strong></td>
<td>$P_{\text{ini}}$</td>
<td>$P_{\text{ini}} + P_{\text{bl}}$</td>
<td>$P_{\text{ini}} + 2.5 \cdot P_{\text{bl}}$</td>
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<tr>
<td><strong>in the 2010’s</strong></td>
<td>100</td>
<td>101</td>
<td>102.5</td>
</tr>
</tbody>
</table>

Table 15: Additional cost of the implementation of mitigation technique in a receiver ($P_{\text{ini}}$ price of the receiver without mitigation technique, $P_{\text{bl}}$ price of blanking)

NB: These figures are supplied for information only and do not bind THALES Avionics in future studies.
9 CONCLUSION - RECOMMENDATIONS

9.1 ISOLATION BETWEEN E5B AND L5

If a receiver uses GALILEO E5b and GPS L5 (usefulness to demonstrate), a 50dB isolation between the two bands with a coarse blanking technique (blanking of strong pulse only) ensures no common failure mode due to DME/TACAN interference. This technical solution induces a 0.3dB loss on the signal to noise ratio.

![Figure 27: Standard interference rejection specification](image)

NB: The coarse blanking might be replaced by proper saturation of the ADC.

This technical solution is compatible with Civil Aviation Requirement.

9.2 ROBUSTNESS TO DME/TACAN AND MITIGATION TECHNIQUE

With the current SIS ICD, a blanking or FDAF technique performs the sufficient signal to noise ratio to ensure robustness in phase tracking (28dBHz) and in acquisition (31dBHz). At high altitude, tracking and re-acquisition (<31dBHz) threshold are the most significant thresholds.

NB: The coarse blanking might be replaced by proper saturation of the ADC.

9.3 THRESHOLDS

There is a need to re-examine operational needs for acquisition in en-route flight, as reacquisition only with positioning from second frequency (E1) may release design constraints.

9.4 TEST ON THE RECEIVER

A test should integrate a DME/TACAN scenario with emission frequency taken at random between plus or minus 10MHz around the central frequency and a power taken at random between −100dBW and −130dBW.

The number of beacons taken depends on the central frequency (E5b or L5) and the worst case (maximum number of beacons in view at the same time). For the decade 2010-2020, more DME beacons than currently should be considered in the test for standardisation (20% more). After 2020, the DME/TACAN beacons will be progressively replaced by other systems like GPS, GALILEO and ILS.
9.5 Accuracy

This document has presented the accuracy or standard deviation on the pseudorange inferior to 0.7m.

These results should be analysed in an overall accuracy budget.

9.6 Isolation of the VHFCOM Air-ground Transmitter

50dB can be made by antenna isolation but a 44dB-rejection filter has to be added to the VHFCOM emitter.

9.7 Deployment Plan of Radar

No deployment plan of radar and precise characteristics (antenna directivity and gain, type of modulation etc) are available. In this context and within this limited study overview, it is not possible to define realistic margins to be taken into account for radar. Results are expected from the other GALILEO projects.
10 APPENDIX 1 : METHODOLOGY USED FOR SIMULATIONS

The methodology used to make the simulation is described on the figure hereafter:

Figure 28 - Methodology used to determine the impact of DME/TACAN on E5b signal
10.1 Precision of Simulation

The precision of simulation depends on the Monte-Carlo statistic process. Our simulation have a plus or minus 7% of precision (±0.6dB on the signal to noise ratio, ±7% on the precision).

The simulation precision is given by the following formulae:

\[
\sigma_{C/NO} (dBCz) = 10 \log_{10}(1 \pm \sqrt[2]{2 \over N})
\]

\[
\sigma_{precision} (%) = \pm {1 \over 2} \sqrt{2 \over N} \times 100.
\]

N is the number of samples on which we make the simulation.
11 APPENDIX 2: DETAILED DME DESCRIPTION

11.1.1 Types of DME

The following characteristics are taken from [AD3], which corresponds to the current DME generation. The old generation, DME/N, is described [AD4].

“N” stands for Narrow spectrum characteristics. They primarily serve the operational needs of en-route or TMA navigation.

“P” stands for precise distance measurement. They are the distance measuring elements of the MLS. The spectrum characteristics are those of DME/N.

DME/P Final approach (FA) mode supports flight operations in the final approach and runway regions.

DME/P Initial Approach (IA) mode supports flight operations outside the final approach region (interoperability with DME/N in this region).

11.1.2 DME disturbing mode

DME and TACAN are pulse ranging navigation systems that operate in the 960-1215MHz frequency band.

An Airborne DME is used to measure the slant range between the aircraft and the DME or TACAN ground beacon. The measurement accuracy is about 0.1NM. A DME ground beacon can manage up to 100 aircrafts.

TACAN, an equivalent military navigation system, provides both azimuth and distance information. DME and TACAN operates in four modes W, X, Y and Z (W, X, Y, Z for DME; X, Y for TACAN).

The DME/TACAN principle rests on an interrogation/answer process. If a plane interrogates a beacon by selecting the DME frequency, the beacon will repeat the signal after a frequency conversion of 63MHz. The emitted signal (from the Airborne beacon) shall be composed of a train of two pulses, while the received signal (from the DME ground beacon) will be characterised by the same train of pulses, i.e. with the same interval between both pulses. The delay between signal emission and signal reception allows the determination of the slant range between the aircraft and the beacon. Even if beacons are not interrogated, they will send 1000 Pulse Pairs Per Second (ppps) (this is called squitter). Squitter aims at maintaining the temperature of the beacon and allows the automatic gain control of the interrogator to work in an optimal band.

The following figure shows the results of the measurement campaign made at Orly airport where a maximum of 1600 pulse pairs per second has been recorded.

---

4 Data have been provided by the STNA (French Air Navigation Technical Service)
Figure 29: Number of pulse pairs per second sent by the DME at ORLY airport (en-route navigation needs)

Characteristics:

Pulse separation and carrier frequencies depend on the mode. [AD3] gives the following:

Date and hour U.T.

Pulse pairs per second
### Interference mitigation techniques for air receivers

<table>
<thead>
<tr>
<th>Channel suffix</th>
<th>Band</th>
<th>Channel spacing</th>
<th>Reply pulse spacing</th>
</tr>
</thead>
</table>
| DME X          | Interrogation: 1025-1087MHz or 1088-1150MHz  
Reply: 962-1024MHz or 1151-1213MHz | 1MHz | 12µs |
| TACAN X        |      |                 |                     |
| DME W          | 979-1017MHz | 2MHz | 24µs |
| DME Y          | Interrogation: 1025-1087MHz or 1088-1150MHz  
Reply: 1088-1150MHz or 1025-1087MHz | 1MHz | 30µs |
| TACAN Y        |      |                 |                     |
| DME Z          | 1041-1080MHz | 1MHz | 15µs |

Table 16: DME/TACAN characteristics for the four modes W, X, Y and Z

Only the DME and TACAN X-mode replies fall in the E5 band.

#### 11.1.3 Time characteristics

The spacing and Pulse Repetition Frequency (PRF) for DME and TACAN X-mode transmitted pulse pairs shall be as given in the following table ([AD3]):

<table>
<thead>
<tr>
<th>Operating mode</th>
<th>Pulse pair spacing (reply)</th>
<th>PRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>DME/N</td>
<td>12µs</td>
<td>2700 pulse pairs per second</td>
</tr>
<tr>
<td>DME/P Initial approach</td>
<td>12µs</td>
<td>2700 pulse pairs per second</td>
</tr>
<tr>
<td>DME/P Final approach</td>
<td>12µs</td>
<td>2700 pulse pairs per second</td>
</tr>
<tr>
<td>TACAN</td>
<td>12µs</td>
<td>3600 pulse pairs per second</td>
</tr>
</tbody>
</table>

Table 17: Pulse Pair spacing and Pulse Repetition Frequency

Remark: The pulse pair spacing is the interval from the half voltage point on the leading edge of the first constituent pulse to the half voltage point on the leading edge of the second constituent pulse.

The pulse envelope as detected by a linear detector has a gaussian shape which has the characteristics noted on the figure below (characteristics come [AD3]):
11.1.4 Pulse spectrum

The spacing between the reply frequencies of two adjacent DME is 1MHz. The pulse spectrum is shown on the figure below (characteristics are taken from [AD3]):
Figure 31: Pulse pair spectrum shape with norm’s specifications
12 APPENDIX 3: DESCRIPTION OF JTIDS/MIDS

12.1 AIM OF THIS SYSTEM

JTIDS/MIDS/LINK16 are a same communication, navigation and identification system intended to exchange surveillance and command and control information among various platform.

12.2 MESSAGE CARACTERISTIC

A MIDS net is based on a TDMA transmission technique. Each terminal is capable of participating in 128 slots per second, where each time slot contains either 72, 258 or 444 pulses depending on the message structure (Round-Trip-Timing, Double Pulse Standard Slot and Packed-2 Single Pulse, Packed 2 Double Pulse and Packed-4 Single Pulse respectively) used for specific timeslot.

12.3 PULSE CARACTERISTIC

12.3.1 Temporal characteristic of one pulse

Each pulse consists of 32, contiguous 0.2-microsecond chips, and pulses are uniformly separated by 13-microseconds symbol structure: 6.4μs microseconds- measured at the 90% power point of pulse information and 6.6μs of pulse shaping and off-time.
Requirements for the temporal pulse shape are:
- The leading edge shall last 1µs maximum.
- The falling edge shall last 1µs maximum.
- An off-time of 2.5µs minimum is required at −80dB.

12.3.2 Spectral characteristic of one pulse
Each pulse’s rise and fall is controlled and the pulse width is measured at the time of transmission to ensure consistent spectral content.

12.3.3 Pulse carrier
The frequency of transmission of each pulse is chosen randomly selected from a set of 51 authorised carrier frequencies in the range of 969MHz to 1206MHz, where the carrier frequencies are spaced at 3MHz intervals, except in exclusion bands centred at 1030MHz and 1090MHz.
### Table 18: Carrier frequencies of JTIDS/MIDS pulses

<table>
<thead>
<tr>
<th>Channel number</th>
<th>Frequency (MHz)</th>
<th>Channel number</th>
<th>Frequency (MHz)</th>
<th>Channel number</th>
<th>Frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>969</td>
<td>17</td>
<td>1062</td>
<td>34</td>
<td>1158</td>
</tr>
<tr>
<td>1</td>
<td>972</td>
<td>18</td>
<td>1065</td>
<td>35</td>
<td>1161</td>
</tr>
<tr>
<td>2</td>
<td>975</td>
<td>19</td>
<td>1113</td>
<td>36</td>
<td>1164</td>
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<tr>
<td>3</td>
<td>978</td>
<td>20</td>
<td>1116</td>
<td>37</td>
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<td>1005</td>
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<td>1053</td>
<td>31</td>
<td>1149</td>
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</tr>
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<td>1056</td>
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<td>1152</td>
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<td>1203</td>
</tr>
<tr>
<td>16</td>
<td>1059</td>
<td>33</td>
<td>1155</td>
<td>50</td>
<td>1206</td>
</tr>
</tbody>
</table>

### 12.4 Timeslot Duty Factor (TSDF)

A TSDF of 100% is defined as the total number of pulses resulting from transmitting 258 pulses in 128 timeslots each second. Thus 100% TSDF equates to an environment of 33024 pulses per second distributed uniformly among the 51 authorised carrier frequencies.

### 12.5 Emission Power

Three levels of power is possible for each pulse:
- 14dBW (25W)
- 23dBW (200W)
- 30dBW (1000W)

Remark: The power given above is the pulse peak power. The mean power is 3dB lower.

All the energy is concentrated on the 3MHz. The limitation of the spectrum is:
Figure 33: JTIDS/MIDS spectrum mask
13 APPENDIX 4 : FDAF MITIGATION TECHNIQUES

13.1 Principle

13.1.1 Introduction
This technique is based on a “frequency blanking” principle. In other word each corrupted frequency is eliminated. It proceeds in three phases:

- Spectral analyses of the received signal to characterise the power spectral density and make difference between corrupted and uncorrupted frequency band.
- Choice of which frequency band is to be blanked, by comparing the power spectral density with a threshold that characterises the ambient thermal noise.
- Applying the spectrally differentiated blanking to the signal

This principle is also named auto-adaptive filtering. It enables the rejection of in band interference by filtering. In order not to filter the whole useful band it only rejects the affected band, which are detected by spectral characterisation of received signal in real time.

The ways to implement this principle in a receiver are multiple and may differ in terms of complexity, reactivity, and rejection performances. Classical solutions lead to implement it digitally. Two options can be chosen: cabled logic (ASIC, FPGA) or software (DSP).

13.1.2 Parameters

13.1.2.1 Threshold determination
The determination of the threshold is done with respect to the ambient thermal noise. As the thermal noise power level follow a Khi² distribution, the blanking threshold is chosen depending on the level of false activation we accept.

In our simulation, we accept less than 0.01% of false activation for a blanking threshold equal to three times the standard deviation of the noise power.

13.1.2.2 Treatment adapted to the interference in time and frequency
Pulsed jammer disturbs the E6 band. FDAF should thus eliminate the interference in time and in frequency. The precision of the treatment in frequency is given by the relation:

$$\Delta f = \frac{1}{N \cdot \Delta t}$$

\(\Delta f\), precision in frequency

\(\Delta t\), precision in time (sample frequency)

\(N\), number of points of the FFT
A precise treatment in frequency is achieved with a low sample frequency and a high number of points used for the FFT.

The precision in time depends on the number of samples used for the FFT:

$$\Delta t = \frac{N}{\Delta f}$$

$\Delta f$, precision in frequency

$\Delta t$, precision in time (sample frequency)

$N$, number of points of the FFT

A precise treatment in time is achieved with a high sample frequency and a low number of points used for the FFT.

A compromise must be found for the number of points with a limit of precision described by the Heisenberg relation:

$$\Delta t \Delta f \geq \frac{1}{4\Pi^2}$$

$\Delta f$, precision in frequency

$\Delta t$, precision in time (sample frequency)

13.1.2.3 Computation load

The FDAF process is divided in four parts:
- Calculate the FFT on a packet of samples of the input signal
- Comparison of the FFT and a given threshold
- Zero the frequencies which are over the given threshold
- Calculate the FFT$^{-1}$

The faster algorithm to compute a FFT has a computation load in $N\log_2 N$, i.e. $2N\log_2(N)$ for a FFT and an inverse FFT, with $N$ the number of points for the FFT.

The comparison with a threshold and the zeroing of the disturbed frequency has a negligible computation load.

In order to maximise the accuracy of the FFT estimation a specific treatment may be necessary, by combining several consecutive FFT for instance. Indeed a rough FFT operation provides a noisy estimation of power spectral density. This induces false alarm and missed detection of interference. This amelioration of FFT estimation induces non-negligible computation load and power consumption.

13.1.2.4 Number of point chosen

Hereafter are the values taken in our simulations. With a 50MHz frequency, we compute the FFT on 64 points in one time (no average to improve accuracy).
GENERAL

13.2 Hypothesis on the HF Architecture

The filtering of in-band interference needs a high dynamic quantification. The necessary number of bits is computed according to the maximum rejection. The link between the number of bits and the rejection is given by the equation below:

\[ D = 6.02 \cdot N_{\text{bits}} + 1.76 \quad \text{dB} \]

For example, a 12 bits ADC allows around 72dB rejection.

Moreover, this high dynamic ADC needs a high quality front-end design to avoid interference mixing and aliasing due to amplifier non-linearity and frequency plan defects.

13.3 Chosen Implementation

13.3.1 Introduction

The FDAF can be implemented in digital either with a DSP or with an ASIC.

13.3.2 Use of a DSP

With the number of points chosen in the previous paragraph 13.1.2.4, the microprocessor needs to have a 3GHz frequency (384 operations in 1.28*10^-7s).

This processor would have high consumption and would probably be expensive even in ten years time.

13.3.3 Use of cabled logic

The use of cabled logic is possible. A FPGA can be developed for the four steps of the FDAF technique. This technique is quick enough.

13.4 Cost

For the present, the additional cost to implement this technique, as described here before, is likely to be more important compared to the basic blanking. It needs a complete new design of the receiver at the front-end level (high linearity of the analogue part + 10-12 bits ADC). If the design of the front-end level is already done for another reason (adaptive antenna for example), the additional cost of FDAF is only due to the computation load for DSP implementation and the additional component/consumption for a FPGA implementation. Nevertheless the evolution of FPGA and DSP cost until 2008 is difficult to establish.
Interference mitigation techniques for air receivers
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