ANALYSIS OF POTENTIAL INTERFERENCE SOURCES AND ASSESSMENT OF PRESENT SOLUTIONS FOR GPS/GNSS RECEIVERS

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ABSTRACT

Many experiments are presently being carried out on the future DGPS-based approach and landing systems to improve the quality of aircraft navigation. The use of C/A-code receivers for aeronautical applications requires high reliability and integrity. This study is an investigation of the potential sources of electromagnetic interference for the Standard Positioning Service of the GPS receivers using the C/A code and navigating inside an avionic environment. Radio-frequency emissions from several communication systems using frequencies adjacent to the GPS and GLONASS bands present considerable problems for the GNSS reception.

An overcrowded frequency spectrum and weak GPS signals make RF interference from a variety of sources a potential threat that must be examined with care.

This paper intends to give an overview of the potential sources of interference and their solutions. These sources of RFI are identified, and the vulnerability of GPS and GNSS to that interference is assessed. The study procures a quantitative comprehension of the impact of interference. The most important sources of interference are studied in terms of their technical characteristics, their jamming distance and the isolation or the rejection requirements needed to keep the good performance of the receiver. Candidate mitigation techniques are also examined, and selected techniques are recommended for adoption in appropriate standards.

Keywords: Interferences, Jammers, GPS, Navigation, Aviation.

1. INTRODUCTION

The typical signal available to the commercial GPS receiver is -160 dBW (-130 dBm compared with -134.5dBm specified by ARINC) at the antenna input, spreaded over about 2MHz bandwidth (8MHz for Narrow Correlator) by the spread spectrum code, at though most of the power can be found in the central 2MHz section. The thermal noise power (kTB) in 2MHz, derived from the Boltzman's constant k (-228.6dBW/HzK), is -141 dBW at 300°K using a perfect receiver, or -137dBW if the radio front end achieves a 4dB noise figure. Thus the receiver starts with a theoretical signal to noise ratio of about -23dB in 2MHz. In practice, the antenna may have a few dB of gain and the GPS Signal level is higher. To give an idea of the received power, -160dBW into 50Ω is equivalent, as a single CW carrier, to about 71nV. A good VHF receiver expects almost a 1µV. But the GPS receiver most take the signal in 2MHz of bandwidth, compared with 25KHz for the VHF communication receivers, so it gets 80 times the noise power. Thus the GPS receiver has to separate a 71nV signal (equivalent) from under about 1µV (-137dBW) of equivalent noise which is quite a challenge. This example illustrates the vulnerability of GPS signal to Narrow Band Interferences and the power levels in consideration in this paper.

Different kinds of jammers can be found if we look carefully in the frequency spectrum of a spread spectrum system which will affect the reception of the useful signal. This paper is not related with analysis of intelligent or non-intelligent jammers rather with occasional interferences.

1.1 IMPACT OF NARROW BAND INTERFERENCES

The Figure 1.1 shows the spectral representation of the situation where GPS signal is in the presence of an interference.

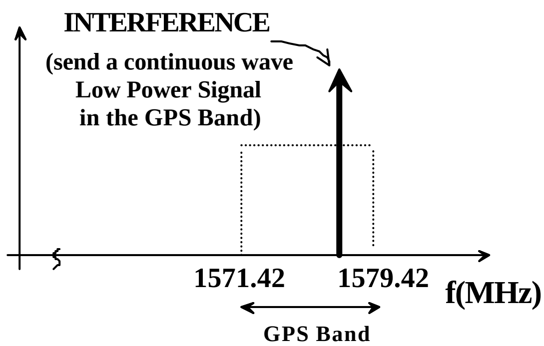

Figure 1.1: Interference in the GPS Band.

4th Saint-Petersburg on INS, May 26-28 1997.

To generate a power level of -115dBW/m^2 in a 100Hz bandwidth at a 15Km range requires a transmitter power of 1 Watt. In practice, in a very small handset equipment, a 1 Watt emitter can jam most of the civil GPS receiver in a perimeter of 30Km from an airport (Ref.[12]). A theoretical analysis will give a better illustration of the problem. The theoretical jamming distance of a narrow band jammer is given by the Equation 1.1.

$$P_J + 20\log\left(\frac{\lambda}{4\pi d}\right) + G_t + G_r = P_{TH} \quad (1.1)$$

where:
P_J is the transmitted jamming power (dBm),
P_{TH} is the susceptibility threshold level (dBm),
G_r is the GPS antenna gain (dBi),
G_t is the transmit antenna gain (dBi),
d is the jamming distance.

An initial prediction of the in-band susceptibility threshold power for a GPS receiver can be calculated using the spread spectrum jamming margin (M_J) and the system processing gain (G_p) given by:

$$M_J = G_p - \left[L_{sys} + \left(\frac{S}{N}\right)_{out}\right] \quad (1.2)$$

and

$$G_p = \frac{f_c}{f_d} = \frac{1.023\text{MHz}}{50\text{Hz}} = 20460 = 43.1\text{dB} \quad (1.3)$$

where L_{sys} is the receiver correlation loss (0.5 to 3dB, typically 2dB).

A $(S/N)_{out}$ of 16dB is required in the carrier tracking loop to demodulate the 50Hz navigation data (BER<10^{-5}). Substituting these figures into Equation 1.2 results in a jamming margin of 25dB. Assuming a weak received GPS signal level of -127dBm for a 0dBi circularly polarized antenna, the susceptibility threshold is estimated to be -102dBm. Thus, at an interference level of approximately -102dBm, the carrier tracking loop should lose lock resulting in the receiver not being able to demodulate the navigation message. This is an extreme scenario analysis compared to the specification of the RTCA/EUROCAE which specifies -126 to -112 dBm (see Figure 1.3).

The GPS receiver figure-of-merit (FOM), which is an indicator of the quality of the received signal from each satellite being tracked, is normally used to categorize the susceptibility threshold. The FOM values range from 0 to 9, with 9 being the best signal quality. The interference effects must be analyzed into two categories: the threshold and the lost of all satellites (LAS). The threshold is defined as the interference signal level (referenced to the receiver input) at which the FOM for at least two satellite signals acquired by the GPS receiver reduces from a level 9 to a level of 7. The LAS condition is defined as the state in which the FOM for all satellites acquired by the GPS receiver reduces to 0 or when the receiver returns to the pre-acquisition mode.

From these definitions, using the maximum specified susceptibility threshold power of -110 dBm, the LAS is calculated to be -101 dBm and using Equation 1.1 with typical antenna gains (G_t=3dBi and G_r=-5dBi at the horizon), the transmit power required to jam a GPS receiver is shown in Figure 1.2 as a function of the distance.

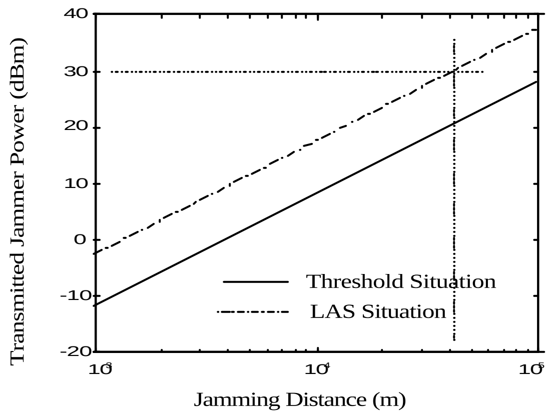

Figure 1.2: Jamming Distance Vs Emitted Power.

This analysis shows that a 1Watt (30dBm) Narrow Band Emitter can theoretically jam a GPS receiver at a distance of nearly 40Km and depending of the GPS receiver, the theoretical model can be adjusted to give a better representation of the reality.

1.2 WORLD WIDESPREAD SPECIFICATIONS

The recognition of this problem has lead to the establishment of the maximum power level of an interference at the antenna of a GPS receiver. Some institutions as ARINC 743A (Ref.[11]), RTCA (Ref.[2]) and EUROCAE have specified the filter performance profile of the out of the C/A GPS band showing the tolerable maximum interference power level. This first specification procures a jamming robustness against the out of band interferences.

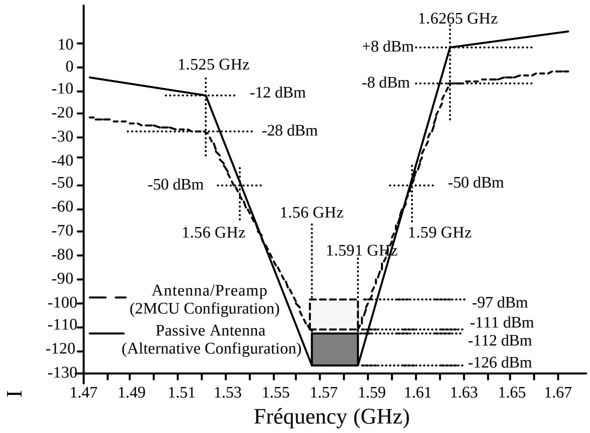

Figure 1.3: Out of the C/A GPS Band Tolerable Maximum Interference Power Level.

Depending of the system combined with the GPS, the overall specifications will change slightly. For example, the out of band rejection for the normal use of the GPS System is shown in the Figure 1.3 and the Figure 1.4 shows the out-of-band pattern for the combined GPS/GLONASS receiver.

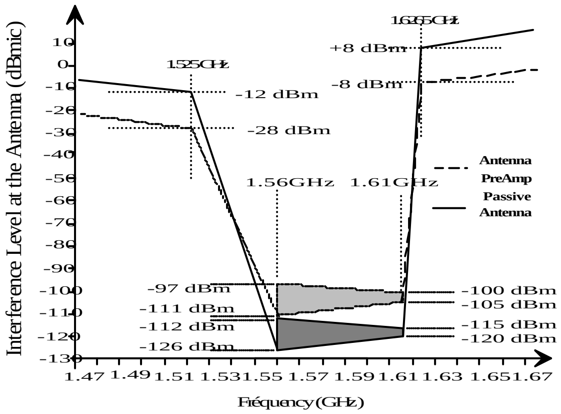

Figure 1.4: Signal Rejection for Combined GPS/GLONASS Signal Rejection.

Remark that the 2MCU Configuration is related with GPS receiver antenna using a PreAmplifier and the Alternate Configuration is for a Passive Antenna. The Figure 1.4 shows clearly that the GNSS receiver will have more interference power because the RF band is larger.

From the same point of view, the Figure 1.5 shows the specification of the GPS in-band interference power not to be exceeded in function of the interference's bandwidth.

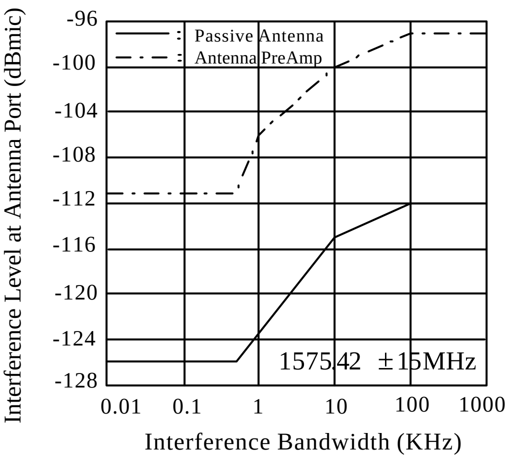

Figure 1.5: Maximum Interference Power Level Tolerable in the C/A GPS Band.

To be effective, an interference signal must be stronger than the ambient noise. The RTCA suggests that power level as low as -126dBm are detrimental to GPS receiver performance. The Figure 1.5 shows also that the C/A code is more susceptible to narrowband interference because of its spectral properties. In fact, due to the line spectral nature of the C/A code, (1msec repetition time and short length), sidebands occur in the code's spectrum at 1KHz intervals, that can lead to false lock being detected in the correlator and code tracking circuits. The result is that the signal processing gain is reduced by several dBs, the exact value depending on the receiver design.

The Figure 1.6 is the in-band specification in the case GLONASS signal.

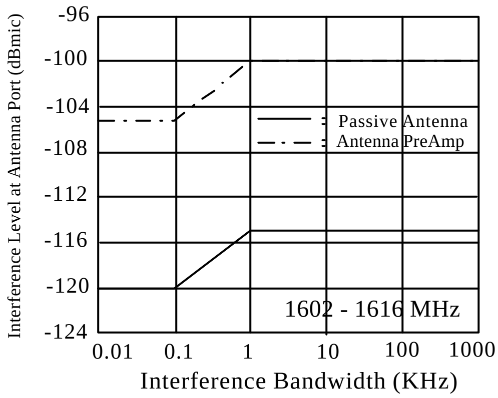

Figure 1.6: GLONASS In-Band Interference Level Requirements (1602-1616MHz).

Moreover, the pulse interference rejection has been specified by RTCA after that a steady state navigation has been established. All classes of equipment shall acquire within 10 seconds and maintain code and carrier lock of a GPS signal in the presence of a pulsed interference having the following characteristics:

- Peak power ≤ 30dBm,
- Pulse width ≤ 100µsec,
- Pulse duty cycle ≤ 10%.

All these values are measured at the input of the antenna port.

2. POTENTIAL SOURCES OF INTERFERENCE

This study concerns non-intentional interferences for the civil GPS receiver. It has been done for the Narrow Correlation GPS Band as defined in the Figure 2.1. All adjacent communication systems to GPS band which is a potential source of interferences have been studied and a summary of the analysis is described in this section.

A potential interference analysis for the GPS military use can also be done with the same technique. The military P code using the 20 MHz band will encounter the same kind of potential non-intentional interferences located in the strict or near GPS band. The perturbation may be greater or smaller but using different parameters, this analysis can also be done on the L2 military application band.

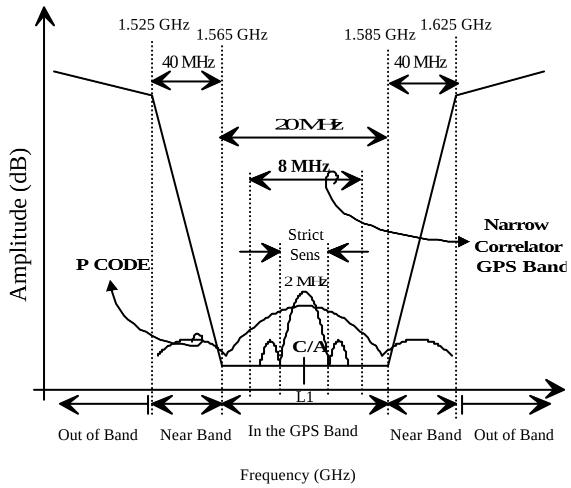

Figure 2.1: GPS Band Definition.

The requirement in terms of the antenna isolation and the RF rejection will be specify for the three main sections of the digital receiver.

For a WidthBand Interference WBI defined as having a Bandwidth much greater than 1KHz (G_{sp}=60dB), the Interference to Signal (I/S) ratio threshold before the C/A code spreading is summarized in Table 2-1:

	Before Spreading
Data Demodulation (BER≤10^{-5})	I/S = 30 dB
DPLL Threshold	I/S = 37 dB
DDLL Threshold (1m/s Doppler precision)	I/S = 44 dB

Table 2-1: I/S Threshold for WB Interferences.

This means that to obtain a BER < 10^{-5}, the ratio of the Interference to Signal power I/S must be 30dB minimum.

For this case only, we call the First Perturbation (the beginning of the degradation) the instant where the signal to noise (S/N) ratio of the GPS receiver has decreased of 3dB $\left(\Delta\left[\frac{S}{N}\right]=-3\text{dB}\right)$. This definition represents the case where the interference power after the spreading gain starts to be greater than the thermal noise plus the receiver noise factor. The Figure 2.2 is an illustration of the first perturbation signification.

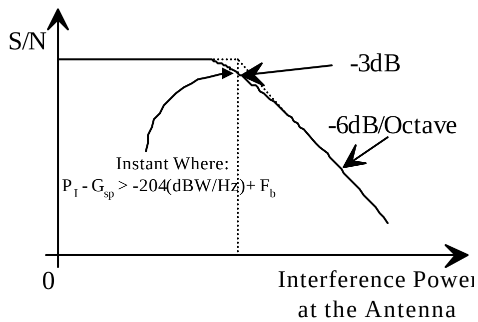

Figure 2.2: S/N fct of the Interference Power.

For a CWI (Continuous Wave Interference), with a spreading gain of 24 dB (due to discrete line spectrum spaced at 1KHz instead of a continuous spectrum), we have the following figures:

	After Spreading	Before Spreading
Data Demodulation (BER≤10^{-5})	S/I = 14 dB	I/S = 10 dB
DPLL Threshold	S/I = 6 dB	I/S = 18 dB
DDLL Threshold (1m/s Doppler precision)	S/I ≅ 0dB	I/S ≅ 24 dB

Table 2-2: I/S Threshold for CW Interferences.

In the case of CWI, the First Perturbation is not representative of the degradation on the receiver. In fact, the frequency location of the CWI within the predetection 50Hz band is the decisive aspect.

Several candidate interference sources can be identified by dividing the GPS C/A Narrow Correlator Band frequencies by the relevant harmonic integer. The Table 2-3 shows the frequency band associated with its harmonic source.

ORDER	BAND (MHz)	USAGE
L1	1571.42 - 1579.42	C/A-GPS
2th	785.71 - 788.71	UHF TV
3th	523.807 - 526.473	UHF TV
4th	392.855 - 394.855	Mobile/Station
5th	314.284 - 315.884	Mobile/Station
6th	261.903 - 263.237	Mobile/Station
7th	224.488 - 225.631	Broadcasting
8th	196.427 - 197.428	VHF TV
9th	174.602 - 175.491	VHF TV
10h	157.142 - 157.942	VHF Maritime
11th	142.856 - 143.584	VHF Military
12th	130.952 - 131.618	VHFCOM
13th	120.878 - 121.494	VHFCOM
14th	112.244 - 112.816	VOR/ILS
15th	104.761 - 105.295	FM
16th	98.214- 98.714	FM

Table 2-3: Sources and Services of Interference v/s Harmonics.

The following of this paper will examine every potential sources of interference for the GPS receiver navigating inside an aeronautical environment.

2.1 Interference Due to VHFCOM Harmonics

The ATC (Air Traffic Control) communication mode uses the [118-137MHz] emission band which correspond to the VHFCOM band. It contains 760 channels spaced at 25KHz. The VHFCOM A/G (Air to Ground) emitted power is 14dBW and 17dBW for the G/A (Ground to Air) mode. Their harmonics are considered as CWI which contain the maximum energy of the VHFCOM signal. The minimum actual harmonic rejections are 54dB for the A/G mode and 57dB for the G/A mode.

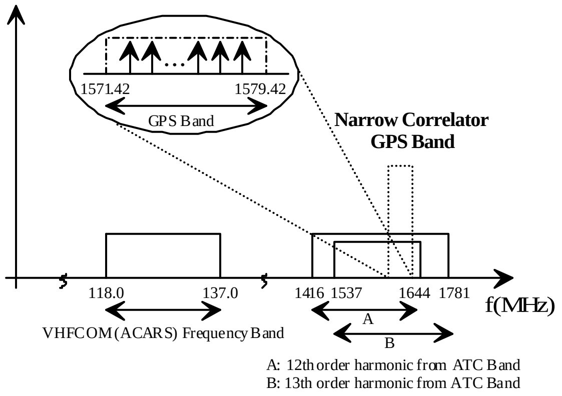

Figure 2.3: VHFCOM Potential Interference.

The Figure 2.3 is the spectral representation of the VHFCOM Potential Interference. It shows that there is 24 channels having the 13[th] order harmonics in the Narrow Correlator GPS Band and 26 channels from the 12[th] order harmonics. Many other harmonics can also be found near this band.

2.1.1 VHFCOM Air to Ground Link Analysis

This scenario occurs when the VHF emitter is on-board the same aircraft of the GPS Receiver. The S/I ratio after the code spreading and at the GPS antenna can be expressed as the following:

$$\frac{S}{I} = S - \left(P_I^{TX} - R_I - ISO - G_{sp} - R\right) \qquad (2.1)$$

where:

$\frac{S}{I}$ = Signal to Interference ratio,
S = GPS Signal (-160dBW for the C/A),
P_I^{TX} = Transmitted Interference Power,
R_I = Rejection at the VHFCOM Emitter,
ISO = VHFCOM/GPS Antenna Isolation,
G_{sp} = Spreading Gain [24dB (90%) for CWI],
R = Out of the GPS Band Rejection (0dB if the Interference is in the GPS Band).

R_I(dB)	Data Demod Threshold	DPLL Threshold	DDLL Threshold
$R_I = 54$	ISO > 110dB	ISO>102dB	ISO > 96dB
$R_I = 60$	ISO > 104dB	ISO > 96dB	ISO > 90dB
$R_I = 90$	ISO > 74dB	ISO > 66dB	ISO > 60dB
$R_I = 100$	ISO > 64dB	ISO > 56dB	ISO > 50dB

Table 2-4: VHFCOM A/G Scenario Analysis.

The Table 2-4 indicates that for the actual minimum harmonic rejection of 54dB, the isolation needed between the GPS and the VHFCOM antennas is 110, 102 and 96dB for the Data Demodulation, DPLL and DDLL Threshold respectively. One recommendation consists to tighten the specification for the VHF transmitter by inserting better filters at the VHFCOM output. This solution must increase the actual harmonic rejections from 54dB to 100dB which will access a feasible isolation. An other mitigation alternative is to install in-band interference cancellation schemes using DSP at the GPS receiver.

2.1.2 VHFCOM Ground to Air Link Analysis

This scenario occurs when an airplane is approching a VHFCOM emitter on the ground. It can be shown that the I/S ratio at the GPS antenna for the Ground to Air scenario is the following:

$$\frac{I}{S} = P_I^{TX} - R_I - 20\log\left(\frac{4\pi d}{\lambda}\right) - R - S - G_{sp} \qquad (2.2)$$

where:

$\frac{I}{S}$ = Interference to Signal ratio,
$20\log\left(\frac{4\pi d}{\lambda}\right)$ = Free Space Loss.

The Table 2-5 indicates a jamming distance from 5m to 5Km depending of the rejection at the VHFCOM emitter and the section affected in the digital GPS receiver.

R_I (dB)	Data Demo Threshold	DPLL Threshold	DDLL Threshold
$R_I = 57$	4800 m	1900 m	950 m
$R_I = 63$	2400 m	950 m	480 m
$R_I = 93$	75 m	30 m	15 m
$R_I = 103$	25 m	10 m	5 m

Table 2-5: G/A Jamming Distance Analysis.

Here again, it is recommended to increase the rejection at the VHFCOM emitter from 57dB to 100dB which will reduce the jamming distance to the order of a few meters or, if it is not possible, to use mitigation technique in the GPS receiver.

2.2 Interference Due to ACARS Harmonics

Three channels from the ACARS (Aircraft Communication Addressing and Reporting System) generate interferences into the GPS and very near the GLONASS bands which may penetrate the in-band filter and hence the GNSS receiver filter may not provide any rejection to this signal.

The Figure 2.4 shows the spectral representation of the ACARS Communication System interfering with the GPS and GLONASS bands. Each channel have 25 KHz of bandwidth and the 12[th] order harmonics are specified to be at a minimum of 28dB down from the carrier EIRP. The ACARS uplink (G/A) transmitted power is 13dBW and the downlink (A/G) maximum power is 14.8dBW.

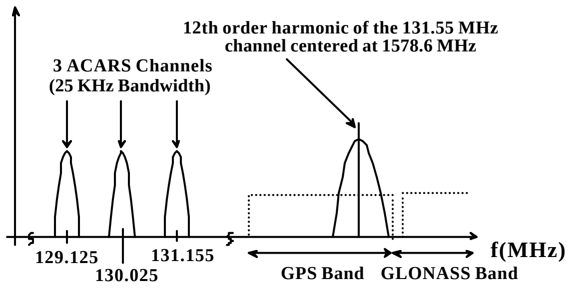

Figure 2.4: ACARS Potential Interference

Because of the configuration's similarity with the VHFCOM, the conclusion of this analysis can be seen directly in the Table 2-6 and Table 2-7.

R_I(dB)	Data Demod Threshold	DPLL Threshold	DDLL Threshold
R_I = 50	ISO > 87 dB	ISO > 79dB	ISO > 73dB
R_I = 60	ISO > 77 dB	ISO > 69dB	ISO > 63dB
R_I = 80	ISO > 57 dB	ISO > 49dB	ISO > 43dB

Table 2-6: ACARS A/G Scenario Analysis.

R_I (dB)	Data Demod Threshold	DPLL Threshold	DDLL Threshold
R_I = 50	270 m	100 m	50 m
R_I = 60	80 m	30 m	10 m

Table 2-7: G/A Jamming Distance Analysis.

In conclusion, the uplink of ACARS is not significant interferer outside of a 270m radius from the emitter. The downlink will cause problems if the antenna isolation is insufficient (less than 90dB).

2.3 Interference Due to VOR and ILS Harmonics

The VOR and ILS Approach Landing Systems are sharing the [108 - 117.95MHz] band including 200 channels frequency spaced at 50KHz. The ILS is using 2 channels on 4 in the [108 - 111.95MHz] band. There is 12 VOR Channels in the [112.24 - 112.816MHz] band which see their harmonics 14th in the Narrow Correlator GPS Band and 2 from the ILS System corresponding to the frequencies 111.90 and 111.95MHz.

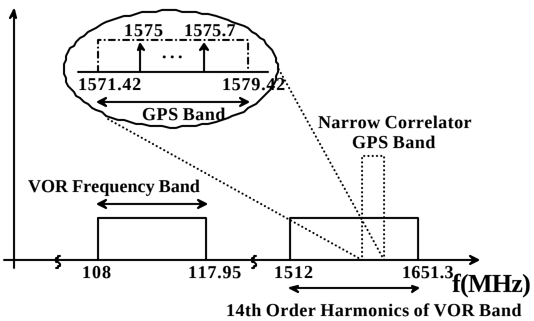

Figure 2.5: VOR/ILS Potential Interference.

Because of their positions in the airport (at the beginning, the end and the sides of the road), VOR and ILS emitters are considered to be a real sources of interference. Moreover, an airplane will pass at a few meters from an ILS emitter which will be more cumbersome than from a VOR emitter.

The continuous signal EIRP of the VOR and ILS is 23dBW for En-route emitter and 17dBW for the ground terminal. Their harmonics are specified to be at a minimum of 60dB bellow the EIRP of the carrier. They are considered as CW/AM interferers. The analysis of a typical navigation configuration is summarized in the Table 2-8.

P_I^{TX}	Data Demod Threshold	DPLL Threshold	DDLL Threshold
23 dB	5380 m	2700 m	1350 m
17 dB	2700 m	1360 m	680 m

Table 2-8: Interfering Distance Analysis.

The conclusion of the study shows that if there is no more restriction for the VOR/ILS emitters, the jamming of a GPS receiver will be observe 5.4Km around an En-route VOR emitter and 2.7Km from a ground terminal. The RF rejection must be 89dB (29dB more than the actual specification) to accept an airplane at 10m from an ILS emitter and 100m from a VOR emitter.

2.4 Interference Due to MODE-S IMP

The Mode-S (Mode Select Beacon System) is a Radionavigation System using 2 fixed frequencies. The interrogator pulsed signal is at 1030MHz and the reply signal at 1090MHz. The maximum transmitted power is 52.5dBW for the interrogator and 27dBW for the reply signal from the aircraft. The Mode-S is considered as a potential pulsed interferer. The characteristics of this source of interference is represented in the Figure 1.6.

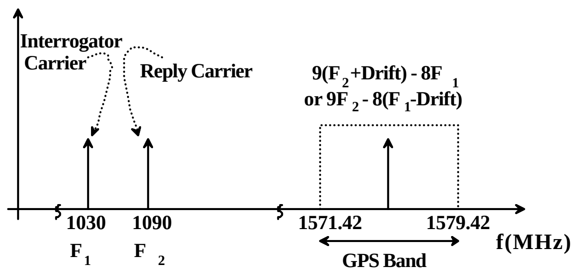

Figure 2.6: MODE-S IMP Interference.

An IMP (Intermodulation Product) will be present in the GPS band if all of the following occur:

- Both the interrogator and reply signal are present at the GPS receiver,
- Both the interrogator and reply pulses overlap,

- A slight frequency drift in either of the carrier frequencies:
  - 0.5 to 0.7MHz drift on the reply carrier,
  - 0.8 to 6MHz drift on the interrogate carrier.
- Without drift, intermodulation occurs at 1570MHz.

The probability of an intermodulation product occurring in the GPS band is very low. Boeing has done statistical analysis of the probability of the offending intermodulation occurring and has dismissed it as a concern.

2.5 Interference Due to Mode-S Side Lobe Power

The Mode-S standard 6365.1A specifies power limits at various frequency off-sets from the carrier. Within the GPS band, the standard requires a minimum power of 60dB down from the carrier for the interrogator and the reply signals.

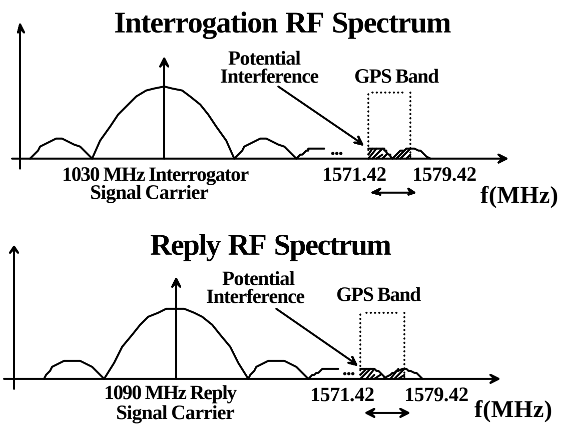

Figure 2.7: Spectral Representation of the MODE-S Interference due to Side Lobe Power.

The maximum transmit time during one GPS bit of 1ms of the interrogator is 95.55µs and 64.55µs for the reply signal. On set of signal degradation due to the side lobe noise occurs when for the interrogator:

$$52.5\text{dBW} - 60 + 10\log\left(\frac{95.5}{1000}\right) - 20\log\left(\frac{4\pi d}{\lambda}\right) \geq -137\text{dBW} \quad (2.3)$$

and for the reply signal:

$$27\text{dBW} - 60 + 10\log\left(\frac{64.55}{1000}\right) - \frac{\text{Antenna}}{\text{Isolation}} \geq -137\text{dBW} \quad (2.4)$$

The conclusion of this analysis is that the side lobe power of the Mode-S will be significant for both interrogator and reply signals. The degradation will be seen if the GPS receiver is at 13.9 Km from a Mode-S interrogator or if the transmitted GPS/Mode-S antenna isolation is less than 91dB. The mitigation alternative is to tighten the out-of-band power limitations on the Mode-S side lobes which could be satisfied with additional 2-poles Butterworth in-line filter.

2.6 Interference Due to the SATCOM Emitters

The SATCOM Communications use the frequency band [1626.5 - 1660.5MHz] as shown in Figure 2.8. The channel bandwidth is 20KHz and they are frequency spaced at 0.75MHz. The mean EIRP is 18dBW and the minimal rejection is 100dB in the L1 band. The SATCOM emitters generate many intermodulation products which can fall inside the GPS band. For example, the channels f_1=1626.5MHz and f_2=1652MHz generate the 5th order IMP $3f_1$-$2f_2$ = 1575.5MHz which is directly inside the L1 band. Both the SATCOM IMP and the proximity of the bands are considered as a real potential source of perturbation. The first part of the analysis treats the IMP interferences and the jamming due to the proximity of the SATCOM band is following.

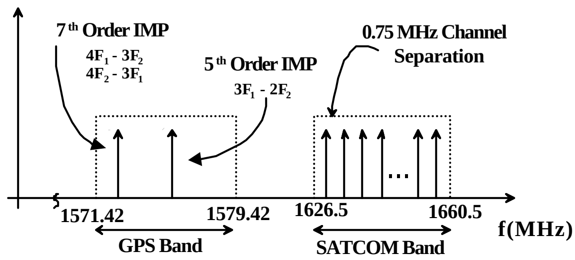

Figure 2.8: Spectral Representation of the SATCOM Intermodulation Interference.

2.6.1 SATCOM IMP Interferences

The SATCOM IMP can be considered as WidthBand Interference (Table 2-1) in the GPS sense because that the carrier wave is only used for the synchronization. For the narrow band jammer analysis, the probability of CW intermodulation is negligible. The isolation between both antennas may respect Equation (2.5) at the First Perturbation.

$$ISO \geq P_I^{TX} - R_I - R - G_{sp} - (-204) - F_b \quad (2.5)$$

Using the Equation (2.1) before the spreading gain and assuming the following figures:

$$F_b = 3\text{ dB} \qquad R_I = 100\text{ dB} \qquad R = 0\text{ dB}$$
$$G_{sp} = 60\text{ dB} \qquad S = -160\text{ dBW} \qquad P_I^{TX} = 18 - 24\text{ dBW}$$

The calculation has been done for the 3rd order IMP which is typically 24dB bellow the carrier's EIRP (ARINC).

	First Perturbation	Data Demod Threshold	DDLL Threshold
C/A	ISO > 35dB	ISO > 24dB	ISO > 10dB

Table 2-9: SATCOM/GPS Antenna Isolation Requirement (on-board the same aircraft).

The Table 2-9 represents the minimum isolation needed between the SATCOM and GPS antennas on-board the same aircraft. The specification of

4th Saint-Petersburg on INS, May 26-28 1997.

ARINC is 40dB and some measurements have shown that the isolation is 50dB minimum. These measurements have been obtained with 1 to 3 meters of separation between the two antennas. Usually, the distance is larger than 3 meters and it can be conclude that there is very low probability to jam a GPS receiver on-board with a SATCOM emitter. Moreover, in the absence of SATCOM emitter in the aircraft, the Free Space Lost is much greater than the 50dB isolation required. After calculation, the jamming distance gives 5m and the conclusion is that the SATCOM IMP can be dismiss as a concern.

2.6.2 Interference due to the Band's Proximity

This analysis concerns the rejection requirement needed by the GPS filter in the SATCOM band. Using the same equations of the previous section 2.6.1 and assuming that:

$$F_b = 3\text{ dB} \qquad R_I = 0\text{ dB} \qquad \text{Isolation} = 50\text{ dB}$$
$$G_{sp} = 60\text{ dB} \qquad S = -160\text{ dBW} \qquad P_I^{TX} = 18\text{ dBW}$$

The Table 2-10 represents the analysis summary of the configuration where the SATCOM emitter is on-board the same aircraft.

C/A	First Perturbation	Data Demod Threshold	DDLL Threshold
Rejec	R > 109 dB	R > 98 dB	R > 84 dB

Table 2-10: GPS Filter Rejection Requirement.

This is the rejection needed by the GPS filter to achieve the S/N ratio requirement. The conclusion is to tighten the GPS filter slope especially for the 1626.5 MHz frequency.

The Table 2-11 concerns the jamming distance due to the nearest SATCOM channel using a GPS filter rejection of 40dB at 40MHz from L1. We use Equation (2.2) before the spreading gain and Equation (2.5) where the isolation between antenna is replaced by the free space loss.

$$20\log\left(\frac{4pd}{l}\right) \geq P_I^{TX} - R_I - R - G_{sp} - (-204) - F_b \qquad (2.6)$$

C/A	First Perturbation	Data Demod Threshold	DDLL Threshold
D_{jam}	13500 m	3800 m	760 m

Table 2-11: Jamming Distance Analysis.
(with R=40dB at 40MHz)

This is one of the most cumbersome situation due to the proximity of the both bands. The GPS preamplifier will saturate and will work in a non-linear mode and it may produces their own IMP. Many attentions on the compression point, isolation between the antennas and the SATCOM band rejection is required.

In conclusion, the problem that would occur if the terminal transmitted on more than one frequency at a time can be dismiss if some precautions on-board the aircraft is performed. The aeronautical SATCOM used for inflight telephones over regions with no terrestrial cells will disturb considerably a GPS receiver due to their band proximities. Non linearity in the transmission equipment then could cause the emission of intermodulation products, same of which could appear in the L1 band. The IMP can also appears to be solved by managing the transmitted frequency selection. One solution is to prohibit passengers'use of multifrequency aeronautical SATCOM during approach and landing operations along with the electronic equipment that could affect critical flight operations.

2.7 Interference Due to TV Harmonics

There is 6 TV channels generating harmonics in the order smaller of 10 which cause interference problem to the GPS receivers. The Table 2-12 shows the French channels and their American equivalents. The Table 2-13 gives an idea of the maximum emitted power.

French Channels	Frequency Band (MHz)	American Equivalents	American Frequency
Channel 4	174-182	VHF 7	174-180
Channel 6	190-198	VHF 10	192-198
Channel 27	518-526	UHF 22	518-524
Channel 28	526-534	UHF 23	524-530
Channel 60	782-790	UHF 66	782-788
Channel 61	790-798	UHF 67	788-795

Table 2-12: TV Channels in Interference.

	Video	Audio
VHF	55 dBW	48 dBW
UHF	67 dBW	60 dBW

Table 2-13: Maximum Emitted Power.

The Figure 2.9 shows the spectral representation of the 2^{nd}, 3^{rd}, 8^{th} and 9^{th} order harmonics of the TV ground stations.

The Table 2-14 shows the main utility of the source of power in interference (video or audio). The jamming distance has been calculated as previously.

The sound carriers of the TV harmonics are considered as CWI in the GPS sense (Table 2-2).

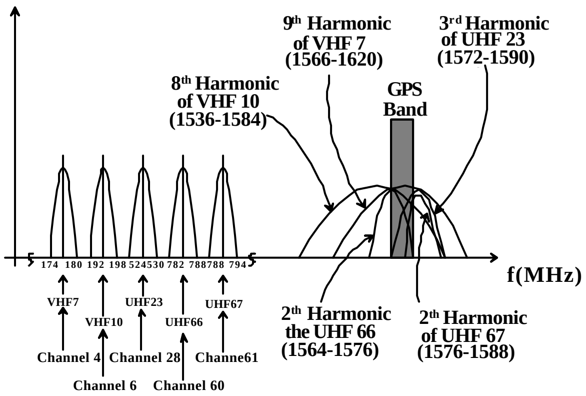

Figure 2.9: TV Potential Interference.

CHANNEL	Interference Power (%)		EIRP (dBW)	Jamming Distance (Km)
	Video	Audio		
VHF 7	5%		42.0	12
VHF 10	5%		42.0	12
UHF 23	11.4%		57.6	72.2
UHF 66		99%	60.0	95
UHF 67	5%		34.0	4.8

Table 2-14: Summary of the Emitted Power and Mean Jamming Distance.

Using the previous Equation (2.2) (G_{sp}=24dB) with the minimal specified harmonic TV rejection R_I of 60dB and assuming that all the energy of the TV harmonic is inside the GPS Band (R=0), the Table 2-15 resumes the jamming distance in function of the miss function of the internal section of the GPS receiver for three sizes of TV emitters.

Type of Emitter	Data Demod Threshold	DPLL Thres	DDLL Threshold
Repeater (1 KW)	15 Km	6 Km	3 Km
Medium (100 KW)	150 Km	60 Km	30 Km
Large (5 MW)	1070 Km	427 Km	214 Km

Table 2-15: TV Jamming Distance Analysis.

The TV emissions are veritable sources of interference for the GPS receiver. Actual restrictions are not sufficients to assure the prevention against jamming. This problem can be solved by local pressures to persuade the TV stations to install inexpensive filters. Because of the high TV emitted power and the unrestriction in some countries, mitigation techniques are also needed in the GPS receiver.

2.8 Interference Due to FM Harmonics

Many small frequency bands inside the FM Band [87.5 - 108MHz] have their harmonics in the GPS Band. The Figure 2.10 shows the spectral representation of the channels 104.9 and 105.1MHz having their 15^{th} harmonics near the NC GPS Band.

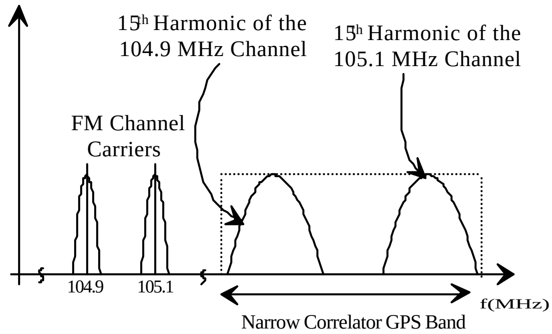

Figure 2.10: FM Potential Interference.

The Table 2-16 shows the FM frequency bands which have their corresponding harmonics in the Narrow Correlator GPS Band (L1 ± 8MHz).

BAND (MHz)		Harmful Harmonics
104.3	105.7	15^{th}
97.8	99.1	16^{th}
92.1	93.2	17^{th}
87.5	88.1	18^{th}

Table 2-16: Harmful FM Harmonics for GPS.

Each channel are spaced at 150KHz and the maximum transmitted FM power is 50dBW. The FM harmonics are considered as widthband interferer in the sense of the C/A GPS signal. The jamming distance analysis in summaries in Table 2-17 using the following parameters:

$$F_b = 3 \text{ dB} \qquad R_I = 80 \text{ dB} \qquad R = 0 \text{ dB}$$

$$G_{sp} = 60 \text{ dB} \qquad S = -160 \text{ dBW} \qquad P_I^{TX} = 50 \text{ dBW}$$

	First Perturbation $(\Delta S/N) = -3$ dB	Data Demod Threshold	DDLL Threshold
C/A	5380 m	1515 m	300 m

Table 2-17: FM Jamming Distance Analysis.

In conclusion, if there is no more restrictions for FM emitters, the uplink FM interference can be significant inside a 5Km radius. One solution is to forbid the use of FM emitters inside a perimeter of 5Km around an airport or increase the rejection at 100dB which will give a reasonable jamming distance of 500m.

2.9 Amateur Radio Harmonic Interferences

The American Amateur Radio Band [220-225MHz] have 4 harmonics of 7th order directly inside the GPS Band and many other are near of it. The emitted power may reach 500W in the United States. The Amateur Radio emitters may not reject their harmonics sufficiently for the GPS applications.

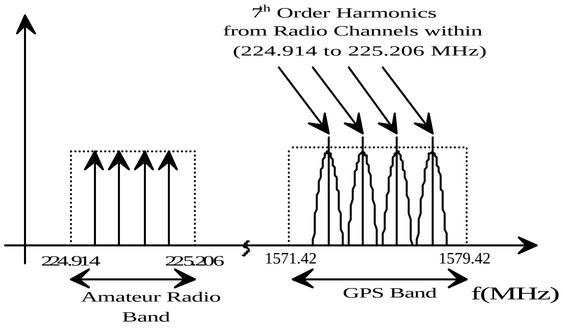

Figure 2.11: Potential Amateur Radio Interference.

The specification shows that the 7th order harmonic must be 60dB bellow the carrier EIRP and in the worst case, they are CWI interference at only 24dB bellow the carrier EIRP.

The jamming distance has been calculated using the Equation (2.2) with the following parameters. The results are summarized in the Table 2-18.

$$F_b = 3\text{ dB} \qquad R_I = 60\text{ dB} \qquad R = 0\text{ dB}$$
$$G_{sp} = 24\text{ dB} \qquad S = -160\text{ dBW} \qquad P_I^{TX} = 27\text{ dBW}$$

P_J^{Tx} 27dB	Data Demod Threshold	DPLL Threshold	DDLL Threshold
C/A	10.7 Km	4.3 Km	2.1 Km

Table 2-18: MSS Jamming Distance Analysis.

The GPS immunity against Amateur Radio Interference will depend on the capacity to reject the 7th order harmonic and the quality of the emitter. From the calculation, a rejection of about 100dB is necessary to cast off from this potential interference. For the European Radio Amateur channels, their emission bands are [144-146MHz], [432-440MHz] and [1296-1300MHz] and they have no harmonic inside the GPS band (L1) except for the military L2 band. This analysis shows potential problem in the United States and that we should dismiss the Amateur Radio Interference as a concern for the civil GPS application in Europe.

2.10 Interferences Due to Future MSS

The MSS System which will operate in the 1610-1626.5MHz band, competes with GPS for spectrum. The handsets transmit voice signal power is approximated to be 0.5W. Actually, it appears that they will be biggest emission violators in the protected L1 navigation bands. Fortunately, they will be located on the ground and may have negligible effects on airborne GPS equipment. MSS interferences are considered as WBI for GPS signal (G_{sp}=60dB). The specifications indicate that the emission MSS rejection will be in the order of 80dB (R_I=80dB).

	First Perturbation	Data Demod Threshold	DDLL Threshold
C/A	R > 82 dB	R > 71 dB	R > 51 dB

Table 2-19: MSS Rejection Band Requirement.

The Table 2-19 shows (using Equation (2.6)) the rejection requirements for the GPS filter at 1610MHz if an aircraft is approaching an MSS emitter at 50m. The same analysis for 150m reduces the rejection of 21dB. A link analyze for the MSS interference to GNSS (Ref.[9]) shows that the MSS remains as the single biggest interference concern to GNSS.

2.11 RADAR Impulsional Interference Analysis

A general analysis of any kind of impulsional interference perturbation is resumed in Equation (2.7). This equation uses the T_{obs} defined as the Observation Time of the perturbation and T_{ttp} which is the Total Time of the Perturbation. This equation corresponds to the S/N ratio after the perturbation.

$$10\log\left[S\left[\frac{T_{obs}-T_{ttp}}{T_{obs}}\right]-10\log\left[N\left[\frac{T_{obs}-T_{ttp}}{T_{obs}}\right]+I\left[\frac{T_{ttp}}{T_{obs}}\right]\right]\right] \qquad (2.7)$$

where:

S = Signal power before the perturbation,
N = Noise power in the loop before the perturbation,
I = Interference power.

$$T_{ttp} = N(T_{imp} + T_{rec})$$

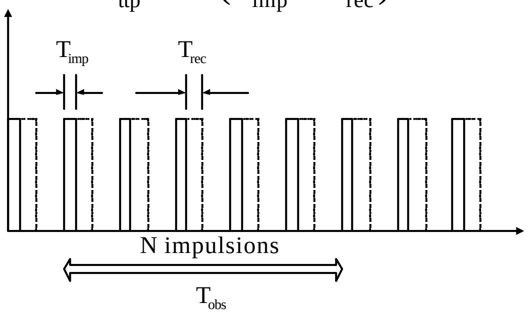

Figure 2.12: Impulsional Signal Definition.

The T_{ttp} includes the total time of all the impulsions and the total time of the GPS receiver recuperation in the observation time as shown is the Figure 2.12.

4th Saint-Petersburg on INS, May 26-28 1997.

The degradation on the S/N ratio can be obtained with the Equation (2.8).

$$\Delta\left(\frac{S}{N}\right)= \quad (2.8)$$

$$10\log\left[\left[\frac{T_{obs}-T_{ttp}}{T_{obs}}\right]-10\log\left[\left[\frac{T_{obs}-T_{ttp}}{T_{obs}}\right]+\frac{I}{N}\left[\frac{T_{ttp}}{T_{obs}}\right]\right]\right]$$

Using this definition, a pulse interferer power limited at -100dBm by the CAN of a receiver which generate pulse at 0.1ms every 10ms will degrade the S/N ratio of 3.2dB maximum. It can be conclude that any radar with a relative ratio smaller than 1% will not disturb the operation of the GPS receiver. The only perturbation can be obtain if the power received at the antenna exceed the destruction power of the diodes before the preamplifier which is in the order of +30 to +45dBm.

Usually, this analysis refers to out of band pulsing systems (such as radar) and will have no significant effect on a GPS receiver.

3. Candidate Mitigation Techniques

In the recent years, many efforts have been done on developing mitigation techniques for Spread Spectrum System. As far as 1960, new theory on optimum procedures for detecting weak signals in noise as been developed by J.Capon. Some works have been followed by digitally implemented adaptive LMS suppression filter for narrow band jammer and so on. Not only the GPS system but also the actual and future system of communication using Spread Spectrum will need effective anti-jamming robustness to improve their reliability.

This section enumerates all the possibility of mitigation techniques for the civil GPS receivers. Their advantages and disadvantages are also listed in the following Tables; the Table 3-1 for the possible Pre-Correlation Techniques and the Table 3-2 for the Post-Correlation Techniques.

3.1 Pre-Correlation DSP Mitigation Techniques:

A) Fixed Frequency Filtering,
B) Adaptive Frequency Filtering,
C) ADP (Amplitude Domain Processing),
D) ADP in Frequency Domain,
E) COLT (Continuous Look Through Filter),
F) ATF (Adaptive Transversal Filter),
G) Adaptive Spatial Nulling Antenna.

	ADVANTAGES	DISADVANTAGES
A	- Low cost. - Simple Technology. - Good for Out-of-Band Interferences	- Not good for In-Band Interferences
B	- Strong efficiency against high power In-Band Jammers.	- Complex architecture against multiple jammers.
C	- Effective against non-gaussien jammers.	- Not effective against multiple jammers. - New technology.
D	- Effective against any kind of jammers (except gaussien). - Good Performance against multiple jammers.	- Tested on P code only. - No publication for C/A codes.
E	- Same as ADP.	- Filter attack time too slow. - Not effective against broadband noise.
F	- 20 to 35dB of gain for narrow band jammer.	- Efficiency not yet performed against other interference.
G	- Effective against large intentional jammers. (Narrow and wideband)	- High cost and size, - Jammer sources difficult to localize.

Table 3-1: Review of Mitigation Techniques.
(Pre-correlation DSP)

3.2 Post-Correlation DSP Mitigation Techniques:

A) Expended Adaptive Code Loop,
B) Vector Tracking Loop,
C) Integrated Inertial Aiding,
D) Adaptive Tracking Loop Bandwidth.

	ADVANTAGES	DISADVANTAGES
A	- Very good performance against broadband gaussien noise.	- Complex Realization or Simulation. - Do not resolve all the problem.
B	- Good multipath response and fast receiver dynamic.	- Item A.
C	- INS is effective against short term jammer.	- High cost and size.
D	- Good for narrowband, - Low cost.	- Small processing gain.

Table 3-2: Review of Mitigation Techniques.
(Post-correlation DSP)

	ACTUAL SPECIFICATIONS			ANALYSIS	RECOMMANDATIONS	
	Transmitted EIRP	Isolation	Rejection R_I	Effect on $D_{jamming}$	Isolation	Rejection at the Tx
VHFCOM A/G	14 dBW	40 dB	54 dB		50 dB	Harmonic Rejections $\geq 12^{th}$ order: 115 dB (C/A)
VHFCOM G/A	17 dBW		57 dB	1 to 5 Km		Harmonic Rejections $\geq 12^{th}$ order: 85 dB (C/A)
SATCOM	18 dBW	50 dB	100 dB		58 dB	Out of Band Rejections 100 dB and $D^{min}_{GPS-SAT} = 5m$
MSS G/A	11.5 dBW		80 dB	200 m		Out of Band Rejections 80 dB of GPS Band
VOR/ILS G/A	17 dBW		60 dB	680m to 2.7 Km		Harmonic Rejections $\geq 14^{th}$ order: 95 dB (C/A)
VOR/ILS A/G	23 dBW		60 dB	1.4 to 5.4 Km		Harmonic Rejections $\geq 14^{th}$ order: 100 dB (C/A)
DME A/G	36 dBW	N.S			36 dB	
TV VHF-UHF	Variable		60 dB	3 Km to Hundreds of Km		Local Pressures to TV Stations to install filters.
FM G/A	50 dBW		80 dB	300m to 5.4 Km		Harmonic Rejections $\geq 15^{th}$ order: 105 dB
Amateur Radio	27 dBW		60 dB	2.1 to 10.7 Km		Harmonic Rejections 7^{th} order: 100 dB (C/A)
Mode-S	27 dBW	N.S.	60 dB	13.9 Km		
ATCRBS	27 dBW	N.S.			27 dB	
ACARS A/G	14.8 dBW	40 dB	25 dB		50 dB	Harmonic Rejections $\geq 12^{th}$ order: 80 dB
ACARS G/A	13 dBW		25 dB	250 m		Increase Rejection to 60dB

Table C.1: Review of Complete Interference Analysis.

GENERAL CONCLUSION

This study of the non-intentional interference for the GPS C/A receiver shows clearly the vulnerability of this Spread Spectrum System. The SATCOM and MSS Systems are the most disturbing sources of interference for GPS receiver but there is also other systems that can be a potential problem for the civil navigation. The jamming distance of each potential Communication Systems near civil GPS applications has been calculated in fonction of the transmitted power, the rejection of the interference emitter in the GPS band and the isolation between both antennas. A summary of all the analysis can be found at the end of this paper.

Many efforts are actually performed to improve and to develop new GPS mitigation techniques. Different kind of techniques are existing as seen before and some of them are actually proposed on the market.

In the future, against unknown interferences, mitigation techniques inside the GPS receiver would have to detect the presence of the interference, to clean the spectrum and to communicate this information to the GPS users.

Along with Anti-jamming Techniques inside receivers, the GPS Interference Monitors will probably be the future equipment needed in the airports to localize any sources of interference. To obtain the integrity, the reliability and the security needed in the aviation when navigating with GPS instrument, such monitors would have the possibility to control emergency vehicles, analogous to fire engines that can go out and stop such transmissions quickly.

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