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TREBALL DE FI DE CARRERA

TÍTOL DEL TFC: Advanced ground based and satellite based precision approach systems.

TITULACIÓ: Enginyeria Tècnica Aeronàutica, especialitat Aeronavegació

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Resum

Aquest treball final de carrera es divideix en dos blocs diferenciats. En el primer d'ells, es farà un anàlisi del sistemes d'aproximació actuals, explicant el seu funcionament, requisits i els avantatges i inconvenients que cada un d'ells aporta. Aquests sistemes es poden classificar alhora en dos grups diferents; per una banda els sistemes que anomenarem clàssics, com són l'Instrument Landing Systems (ILS) i el Microwave Landing System (MLS). Per l'altra, els nous sistemes d'aproximació que utilitzen sistemes de posicionament global per satèl·lit, sempre amb l'ajuda de sistemes d'augment per garantir requeriments de precisió i integritat. Aquests últims són el Satellite Based Augmentation System (SBAS) i el Ground Based Augmentation System (GBAS).

A continuació el treball es centra en el sistema GBAS i hi analitza el seu funcionament i els subsistemes en que es divideix. Es comenten també les diferents font d'error del sistemes GNSS, quines d'aquestes podran ser corregides, i finalment com es generen les correccions que seran enviades a l'aeronau.

El segon bloc se centra en l'anàlisi del receptor VHF Data Broadcast (VDB) embarcat, el qual rep les correccions que crea el sistema GBAS. Aquest receptor segueix el model d'un receptor superheterodí i en el treball s'explica el funcionament de cada un dels blocs que el formen; com són els diferents filtres, amplificadors, mescladors i sintetitzadors de freqüència; així com les seves característiques i requisits. També es realitzen els càlculs per comprovar que es compleixen els requisits implantats per l'Organització d'Aviació Civil Internacional (OACI) en quant a potencies de transmissió i que, per tant, el receptor es apte.

En l'últim capítol del treball es realitza la simulació de tots els blocs del receptor mitjançant el software AdvanceDesign System (ADS) i es comparen els resultats obtinguts amb els càlculs realitzats anteriorment.

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Overview

This final degree project is divided in two differentiated blocks. In the first one, an analysis of the actual landing systems is made, explaining how they work, their requirements and the advantages and disadvantages of each one. Those systems can be classified into two different groups; on one side the systems that we will call as “classic systems”, which are the Instrument Landing System (ILS) and the Microwave Landing System. On the other side, the new approach systems which use global navigation satellite systems, with the support of augmentation systems in order to ensure the definite levels of precision and integrity. Those systems are the Satellite Based Augmentation System (SBAS) and the Ground Based Augmentation System (GBAS).

Next, the project focuses in the GBAS system and analyses how it works and the subsystems that form it. Also the GNSS error sources are commented and whether them can be corrected or not. Finally how the corrections which will be send to the aircraft are generated is explained.

The second block focuses on the analysis of the on board VHF Data Broadcast (VDB) receiver, which gets the corrections generated by the GBAS system. This receptor follows the scheme of a superheterodyne receiver and in the project it is explained how each of the blocks that form it work. These blocks are the different filters, amplifier, mixer and frequency synthesizer and their characteristics and requirements are exposed. Also the calculus to check that the requirements of transmitted power fixed by the International Civil Aviation Organization (ICAO) are made to test out the suitability of the receiver.

In the last chapter of the project, a simulation of the blocks of the receiver is made using the software Advance Design System (ADS) and the obtained results are compared with the values of the calculus made before.

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DH	Decision Height
DME	Distance Measurement Equipment
DME/P	Distance Measurement Equipment Precision
D8PSK	Differential 8-Phase Shift Keying
EGNOS	European Geostationary Navigation Overlay Service
FAR	Federal Aviation Regulations
FAA	Federal Aviation Authority
FAS	Final Approach Segment
FEC	Forward Error Correction
GBAS	Ground Based Augmentation System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRAS	Ground-based Regional Augmentation System
GS	Glide slope
HA	Horizontal Accuracy
HAL	Horizontal Alert Limit
ICAO	International Civil Aviation Organization
IFR	Instrumental Flight Rules
ILS	Instrumental Landing System
IRU	Inertial Reference Unit
LAAS	Local Area Augmentation System
MLS	Microwave Landing System
MMR	Multi-Mode Receiver
NDB	Non Directional Beacon
PPS	Precise Positioning System
PRC	Pseudo- Range Correction
RNP	Requirement Navigation Performance
RTCA	Radio Technical Commission for Aeronautics
RVR	Runway Visual Range
SA	Selective Availability
SBAS	Satellite Based Augmentation System
SPS	Standard Positioning Service
SSID	Station Slot Identifier
TTA	Time To Alert
VA	Vertical Accuracy
VAL	Vertical Alert Limit
VDB	VHF Data Broadcast
VFR	Visual Flight Rules
VHF	Very High Frequency
VOR	VHF Omnidirectional Range
WAAS	Wide Area Augmentation System
WADGPS	Wide-Area Differential GPS

INTRODUCTION

ILS, which was developed in the early thirties, is the main landing system used nowadays in hardly all the airports all over the world. Even though it has been proven as a perfectly safe system, since the decade of the seventies new systems started to develop in order to overcome some of the limitations that it presents.

The first system that appear was MLS, which became operational in the 1990s. Some of the advantages that it supposed in front of ILS were that it incorporated smaller antennas, due to using a higher frequency signal and those did not have to be located at a specific point at the airport, what leads to a reduction in the costs. Also the new system allowed to create new approach configurations such as segmented and flexible landing paths. However, the widespread of this system never became a reality, although it is still in use in some airports in United Kingdom, because of the new generation of satellite systems.

The development of global navigation satellite systems, combined with augmentation systems, are meant to be the prevailing systems in the near future. Among the advantages that these systems account include a reduction in the costs in the airport infrastructure (SBAS systems do not require any) while obtaining the same level of positioning detail, and the capability of producing different approach paths at the same time, increasing the capacity of the airport.

All these is explained in the first part of the project. Next, the project will focus in the GBAS system and more specifically in the design of the front end part of the on-board VDB receiver and a simulation of it will be made using the software Advanced Design System.

Chapter 1. Ground based aircraft landing systems

1.1. Visual Flight Rules and Instrument Flight Rules

The approach phase-of-flight can be developed in two kinds of ways, with Visual Flight Rules (VFR) and with Instrument Flight Rules (IFR).

In the first one, the pilot has to manage to land the plane solely by visual references. The conditions for ceiling and visibility are defined in FAR part 91.155 and they vary depending on the type of airspace in which the aircraft is operating and if it is daytime or nighttime. Typical VFR minimums is 3 statue miles of flight visibility and a cloud distance of 500 ft below, 1000 ft above and 2000 ft horizontally.

When using Instrument Flight Rules, the pilot is helped with different instruments in the flight deck and navigation is accomplished by reference to electronic signals. The systems that follow IFR can be divided in two, non-precision approach systems and precision approach systems.

1.2. Non precision approach systems

The main characteristic about a non precision approach system is that it does not provide electronic vertical course guidance. Those approaches are pilot-interpreted and make use of ground beacons such as VOR, NDB and the localizer of the ILS system, in combination with DME for range. ICAO defines on its Annex 10 the performance requirements for non-precision approaches, which are defined in the next table.

Horizontal accuracy	Integrity Level	Continuity	Availability	Horizontal Alert Limit	Time to Alert
220 m	$1\text{-}1\times10^{7}$/ hour	$1\text{-}1\times10^{-4}$/ hour to $1\text{-}1\times10^{-8}$/ hour	0.99 to 0.99999	556 m	10 s

Table 1.1 Performance requirements for non-precision approaches [1]

The first fourth parameters of the table are known as Required Navigation Performance (RNP) parameters and they describe the requirements of performance for all the phases of flight, and are described by the ICAO on its Manual on Required Navigation Performance as:

- Accuracy: The degree of conformance between the estimated or measured position and/or the velocity of a platform at a given time and its true position or velocity. It is specified as:
    - Predictable: The accuracy of a position in relation to the geographic or geodetic coordinates of the earth.

- Repeatable: The accuracy with which a user can return to a position whose coordinates have been measured at a previous time with the same navigation system.
- Relative: The accuracy with which a user can determine one position relative to another position regardless of any error in their true position.

- Integrity: The ability of a system to provide timely warnings (alert time) to users when the system should not be used for navigation. The navigation system should be able to provide error bounds in real time under every condition.

  Contrary to accuracy, it is not measurable and is expressed as the probability of when the system should not be used per hour. The integrity risk is the probability of an error or an undetected navigation error system failure to provide misleading information.

- Continuity: The ability of the system to perform its intended function and provide the accuracy and integrity required without interruption during the intended operation, if it did so at the beginning of the operation.

- Availability: Indication of the ability of the system to provide usable service within the specified coverage area. Is defined as the portion of the time during which the system is to be used for navigation during which reliable navigation information is presented to the flight crew, autopilot or other system managing the flight of the aircraft.

  The system is available when the Vertical Protection Level (VPL, an estimated bound of error for the vertical position) is lower than the Vertical Alert Level (VAL); and the Lateral Protection Level (LPL, an estimated bound of error for the horizontal position) is lower than the Lateral Alert Limit.

1.3. Precision approach systems

On other hand, precision approach systems also offer vertical guidance besides horizontal. There are two systems that nowadays fulfill those requirements, which are ILS and MLS, excepting the satellite systems, which will be discussed in the next chapter.

The requirements for those approach systems are:

- Accurate and stable guidance from a pre-defined point in space to the runway.
- High reliability.
- Timely detection of system faults.

The integrity and reliability are determined by the system architecture and the permission to continue to land in reduced visibility is determined by decision height (DH), which depends on the ground infrastructure and the on-board landing system. In this decision height, the pilot must abort the landing if the runway is still not in sight.

The next table classifies the categories of service depending on the decision height and the Runway Visual Range (RVR), and are represented in the graphic.

Category	Decision Height (DH)	Runway Visual Range (RVR)
CAT I	≥ 60 meters	≥ 550 meters
CAT II	30 <DH<60 meters	>350 meters
CAT IIIa	DH<30 m or no DH *	>200 meters
CAT IIIb	DH<15 m or no DH **	50 m<RVR<200 meters
CAT IIIc	No DH	No limitations

Table 1.2 DH and RVR for the different categories of service.[1]

* *Decision height for CAT IIIa operations depends on runway visibility. If RVR is larger than 213 m, DH should be at least 30 meters; otherwise there is no decision height.*

***The same occurs for CAT IIIb. If RVR is larger than 50 m, DH should be at least 15 m, otherwise there is no restriction in decision height.*

Figure 1.1 shows the minimum decision height for the different categories.

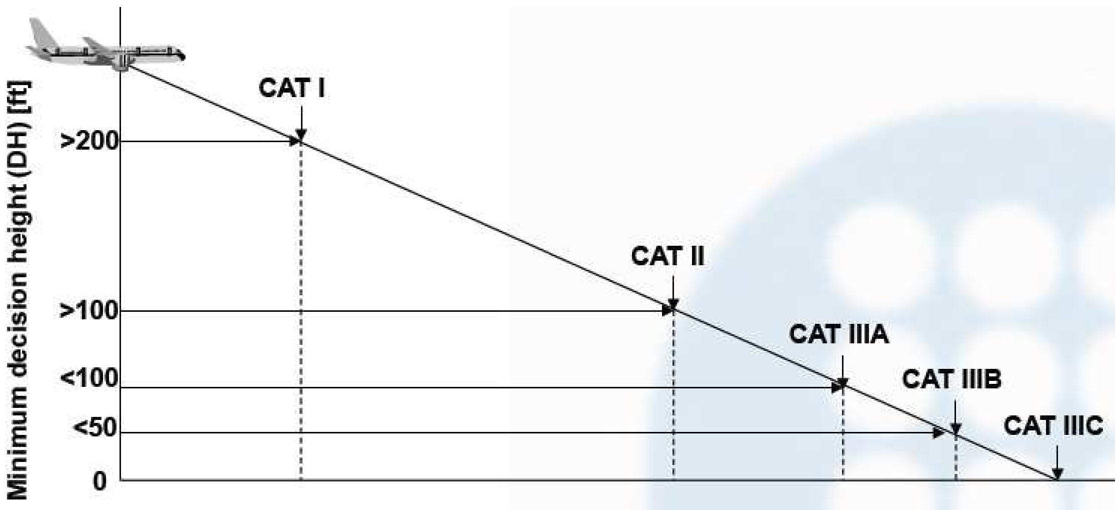

Fig.1.1 Decision height for the diferent categories. [2]

ICAO also defines the requirements for approach systems depending on the categories mentioned before:

	HA (95%)	VA (95%)	Integrity Level	HAL	VAL	TTA	Cont.	Av.
CAT I	10 m	3 m	$1-10^{-7}$	40 m	10 m	2 s	$1-4x10^{-6}$ 15 sec	0.99 to 0.99999
CAT II	5 m	1.2 m	$1-0.5x10^{-9}$	17.3 m	5.3 m	1 s	$1-2x10^{-6}$ 15 sec	0.99 to 0.99999
CAT IIIa	5 m	1.2 m	$1-0.5x10^{-9}$	17.3 m /15.5 m	5.3 m	1 s	$1-2x10^{-6}$ 15 sec	0.99 to 0.99999
CAT IIIb	5 m	1.2 m	$1-0.5x10^{-9}$	-	-	1 s	$1-2x10^{-6}$ 15 s (loc) 30 s (GS)	0.99 to 0.99999
CAT IIIc	5 m	1.2 m	$1-0.5x10^{-9}$	-	-	1 s	$1-2x10^{-6}$ 15 s (loc) 30 s (GP)	0.99 to 0.99999

Table 1.3. Performance requirements for precision systems.[1]

1.3.1. Instrumental Landing System

The Instrumental Landing System is a precision runway approach aid that uses two radio beams to provide pilots with vertical and horizontal guidance during the landing approach. This system, which has developed in the 30s and has been in service since then, has a perfectly save record; ILS has never been blamed for an aircraft accident during normal ILS operation [2].

Even though, the ILS system has some limitations, which have led ICAO to look for other systems, like MLS first, and augmentation systems later.

- As the antenna beams are static, only one straight approach path is offered.
- The number of channels is limited to fourty.
- A large infrastructure is required.
- Each runway requires an independent ILS installation.
- The frequency bands can be interfered with other radio signals, specially the FM band.
- Reflections from buildings, terrain, airborne and taxiing aircraft can induce in multipath errors.
- Big separation required for operations in parallel runways, up to 5.000 ft., for ensure security.

The ILS is formed by the next components:

- Localizer:

An antenna located at the end and on center line of the runway, provides the lateral guidance. It works in a frequency between 108 and 112 MHz and has a range of 25 NM at 10° and 17 NM at 35°.

The carrier frequency is amplitude modulated with a 90 Hz and 150 Hz carrier so, due to the antenna pattern, the 90 Hz signal is dominant on the left side of the runway and the 150 Hz signal dominates the right side. With this information, the deviation from the reference center line of the runway is measured.

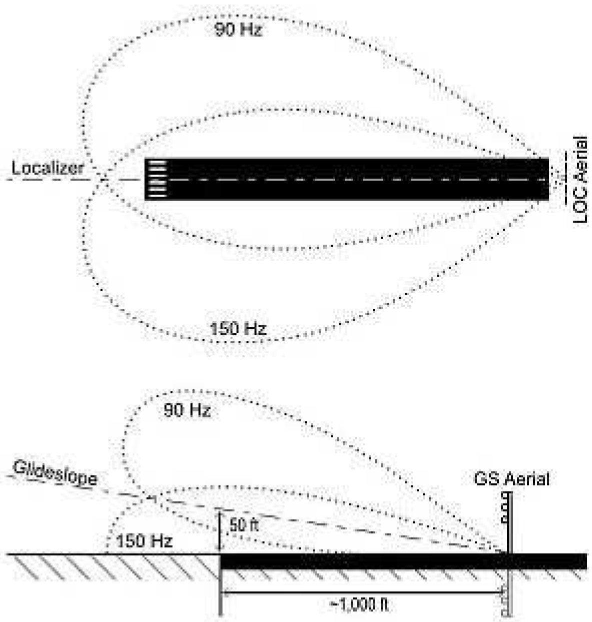

Fig 1.2. ILS localizer and glideslope.

- Glide path or glide slope.

Located besides the runway, near threshold, and working in frequencies between 329.3 and 335.0 MHz, provides vertical guidance with a descent slope of 3° to the runway.

The operating system to obtain the deviation is analog as for the localizer, but this time the antenna pattern makes the 90 Hz signal more powerful when the aircraft is above the correct glide slope and the 150 Hz carrier is stronger when it is below.

- Marker beacons.

Those beacons, located along the approach path at 4 NM, 3500 ft and 100-1500 ft, give information about the distance to the runway threshold. Nowadays, those beacons have been substituted in many installations for DMEs, which provide the distance of the receiver to the station continuously.

- Monitors.

The only function of those monitors is to shut down or switch to back up the ILS when a failure in the system is detected.

1.3.2. Microwave Landing System

The MLS (Microwave Landing System) was developed during the seventies as a system that would overcome the limitations that presented the ILS.

This system, which works in the microwave band (between 5031.0 and 5190.7 MHZ) uses a technique called Time Reference Scanning Beam (TRSB).In this system, the beams of the antennas (one for elevation and one for azimuth), which are narrow in one direction and wide in the perpendicular, scans the space side to side in both directions. So, in every scan cycle, the plane receives two pulses, on in the "TO" scanning and the other from the "FRO". Measuring the time between those pulses, the receiver can calculate its angular position.

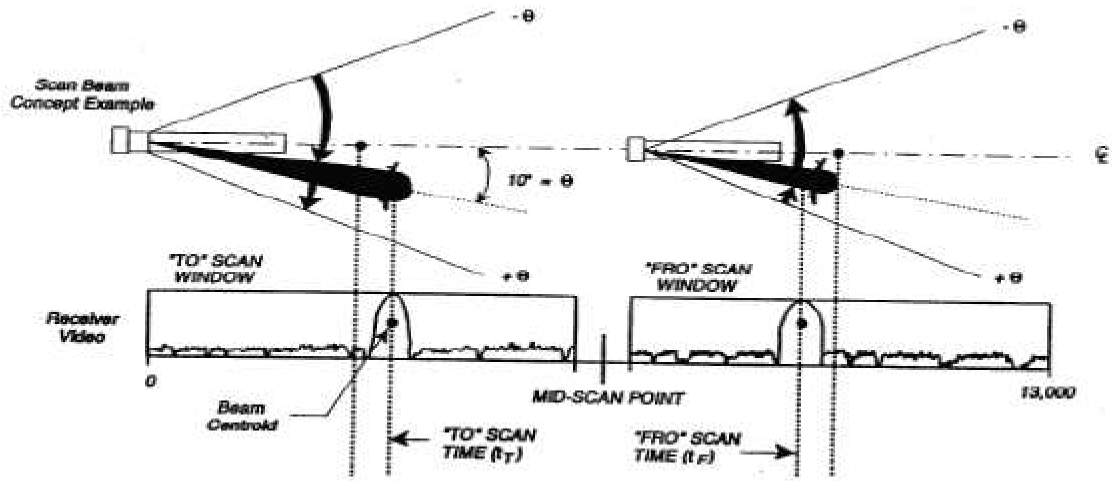

Fig. 1.3 MLS functioning scheme [3]

The system also includes a DME/P for knowing the range and a back azimuth antenna for missed approach operations.

The advantages with respect to ILS are several:

- The number of channels is bigger, up to 200.
- The antennas are smaller due to the fact of using higher frequencies.
- More approach configurations are possible, including flexible landing path, so the capacity of the runway increases.
- No interferences appear due to the frequency in use.

Nevertheless, this system has not been widely used due to the improvements in GPS-based systems. Those systems are able to offer the same level of precision with lower costs and less equipment needed in the airport, non-existent in case of SBAS. They will be described in the next chapter.

Chapter 2. GNSS augmentation systems

2.1. Introduction

A single frequency SPS GPS user can obtain better than 10 meters, 95% positioning and 20 nanoseconds 95% timing accuracy worldwide [4]. In spite of this, some phases of flight, like in our case precision approach landings, demand levels of accuracy that neither PPS GPS nor GNSS can deliver. For this reason, it is necessary to use augmentation systems.

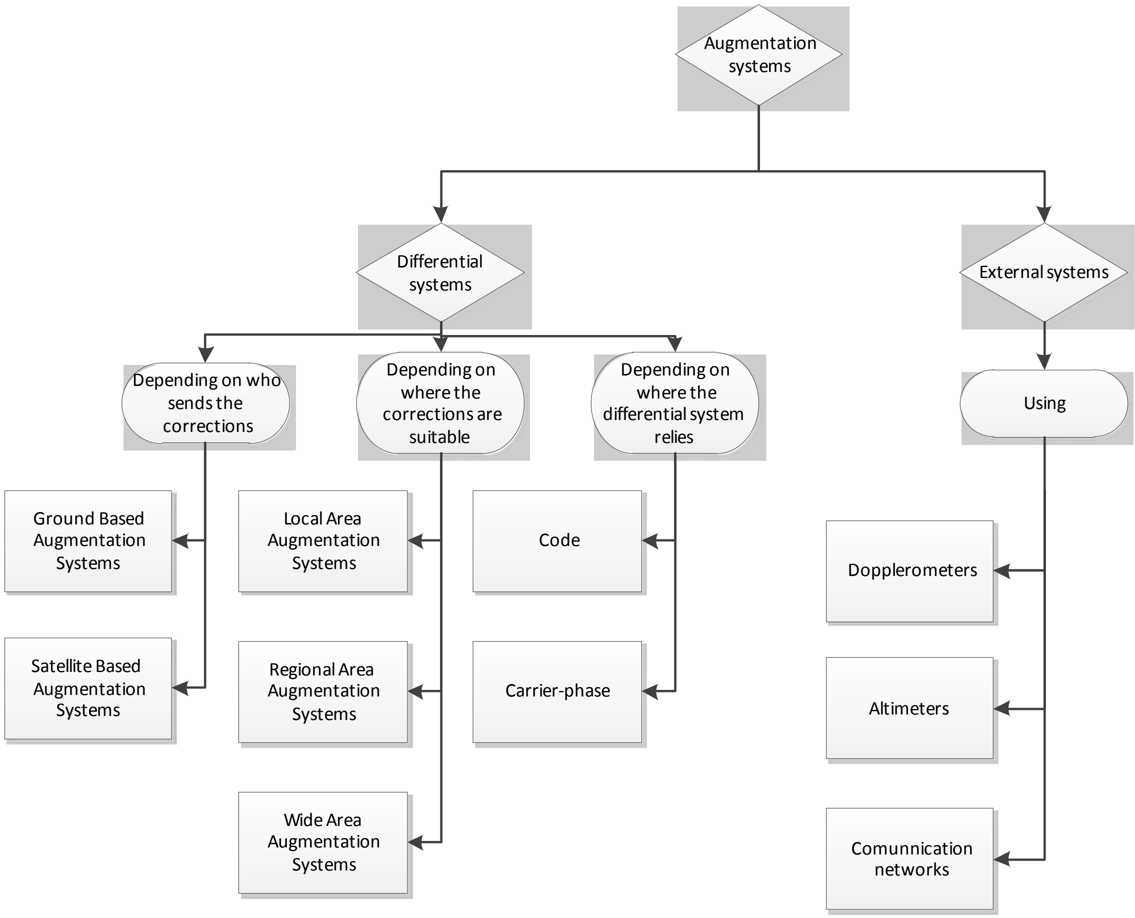

Fig. 2.1 Augmentation systems classification

Augmentation systems can be divided into differential systems and external sensors/systems.

Differential systems are a method to improve the performance of GNSS using one or more reference stations at known locations, which send the corrections and other useful information to receivers via data link. The information send by the reference station, which is typically in any frequency of the band between 300 KHz and 2 GHz, includes:

- Corrections to the raw end user's pseudorange measurements, corrections to GNSS satellite-provided clock and ephemeris data, or data to replace the broadcast clock and ephemeris information.
- Raw reference station measurements.
- Integrity data.
- Auxiliary data including the location, health and meteorological data of the reference station(s).

The fact that is used for the improving of the system performance is that some error sources are highly correlated between space and time. Nearby users in space and time will share a similar satellite-clock, ephemeris and tropospheric and ionospeheric delay errors, so the reference station can compute the corrections and send it to the receivers. This topic will be explained in the next chapter.

Those systems cannot correct other errors like multipath or receptor noise errors due to that those are not shared between the reference station and the users and can vary fast in time.

Differential systems can be divided into ground or satellite augmentation systems, which will be discussed later in this chapter, and local area or wide area augmentation systems. A last division can be done depending on where the differential system relies primarily, if on code measurements or in carrier-phase measurements.

Using external sensors provides the user with continuous navigation, thanks to the integration of GNSS with some of those additional sensors. The most common are inertial sensors, but also dopplerometers, altimeters, speedometers can be used with this finality. Communication networks can also be used to integrate a SPS sensor.

ICAO has established the performance requirements for the satellite navigation systems for the phases of approximation and landing in the document "International Standards and Recommended Practices" Annex 10 and are the following:

	HA. (95%)	VA (95%)	Integrity level	HAL	VAL	TTA	Cont.	Avail.
NPA	220 m	20 m	$1\text{-}2\text{x}10^{-7}$	556 m	20 m	10 s	$1\text{-}8\text{x}10^{-6}$ /15 s	0,99 to 0,99999
APV I*	220 m	20 m	$1\text{-}2\text{x}10^{-7}$	556 m	20 m	10 s	$1\text{-}8\text{x}10^{-6}$ /15 s	0,99 to 0,99999
APV II*	16 m	8 m	$1\text{-}2\text{x}10^{-7}$	16 m	8 m	6 s	$1\text{-}8\text{x}10^{-6}$ /15 s	0,99 to 0,99999
CAT I	16 m	6 m to 4 m	$1\text{-}2\text{x}10^{-7}$	16 m	6 m to 4 m	6 s	$1\text{-}8\text{x}10^{-6}$ /15 s	0.99 to 0.99999

CAT II**	-	-	$1-10^{-9}$	-	-	1 s	$1-4x10^{-6}$ /15 sec	0,99 to 0,99999
CAT IIIa**	-	-	$1-10^{-9}$	-	-	1 s	$1-4x10^{-6}$ /15 s	0,99 to 0,99999
CAT IIIb**	-	-	$1-10^{-9}$	-	-	1 s	$1-2x10^{-6}$ /15s (lat.) $1-2x10^{-6}$ /30s(ver.)	0,99 to 0,999999

Table 2.1 Performance requirements for GNSS augmentation systems. [1]

**APV I and APV II are a new lateral precision approximation with vertical guidance.*

** The requirements for CATII/III have not been defined and validated by ICAO yet. The table shows the ones that were defined for ILS/MLS. It is intended that it will be done on 2015. [5]

2.2. SBAS

Satellite Based Augmentation Systems are a WADGPS that provide differential GNSS corrections using a geostationary satellite as the communication path.

The GBAS user receives the GNSS navigation signals, which are also received by the network of SBAS stations, equipped with GNSS receivers (more than one for redundancy) that provide L1 C/A code and L2 P(Y) code pseudoranges and carrier-phase data to the central processing station. This station receives the data from the whole network and processes it to obtain the correct position and clock error of each satellite. Then it calculates the corrections comparing the known position of the reference stations with the values in the GPS navigation data, including an estimation of the vertical ionospheric delay error across the service area. The central processing station also checks the GNSS satellites and informs if any of them should not be used.

This integrity and correction information is then sent to the satellite uplink facilities, where the spread spectrum navigation signal is generated and modulated with the SBAS data and then transmitted continuously to a geostationary satellite. This satellite finally transmits it to the user on the GPS L1 frequency.

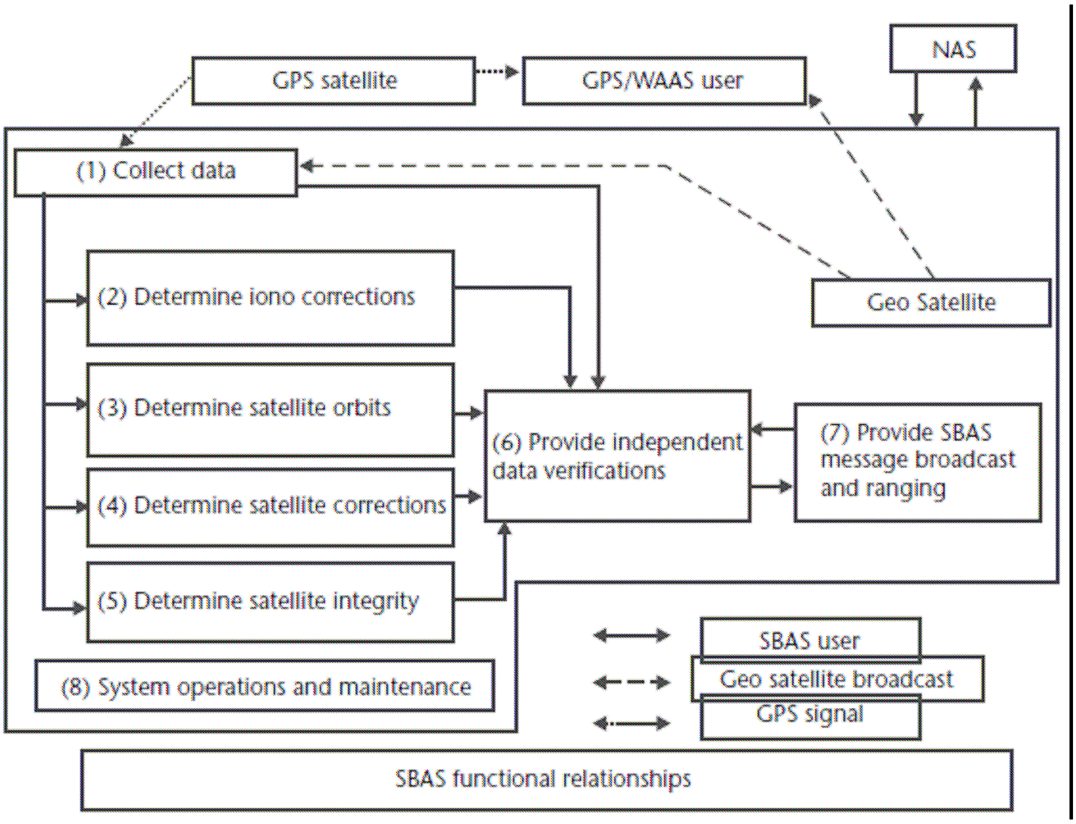

Fig. 2.2. SBAS functional overview. [4]

2.2.1. WAAS

The Wide Area Augmentation System is the SBAS developed by the Federal Aviation Administration to work in North America. It is composed by 59 Wide-area Reference Stations (WRS) (January 2011), spread all over United States, Canada and Mexico, which collect the information on the GPS signals and send it to one of the three Wide-Master Stations using communications network. Finally, four Ground Uplink Stations transmit the corrections messages to the geostationary satellites. [6]

WAAS signal was activated for general aviation on July 10, 2003 covering 95 % of the United States and portions of Alaska (the total coverage of Northern latitudes is difficult due to the use of geostationary satellites), but it was not until December 30, 2009 when the first passenger service flight used WAAS with LPV instrument approach. The flight was operated by the company Horizon Air with a Bombardier Q400. [7]

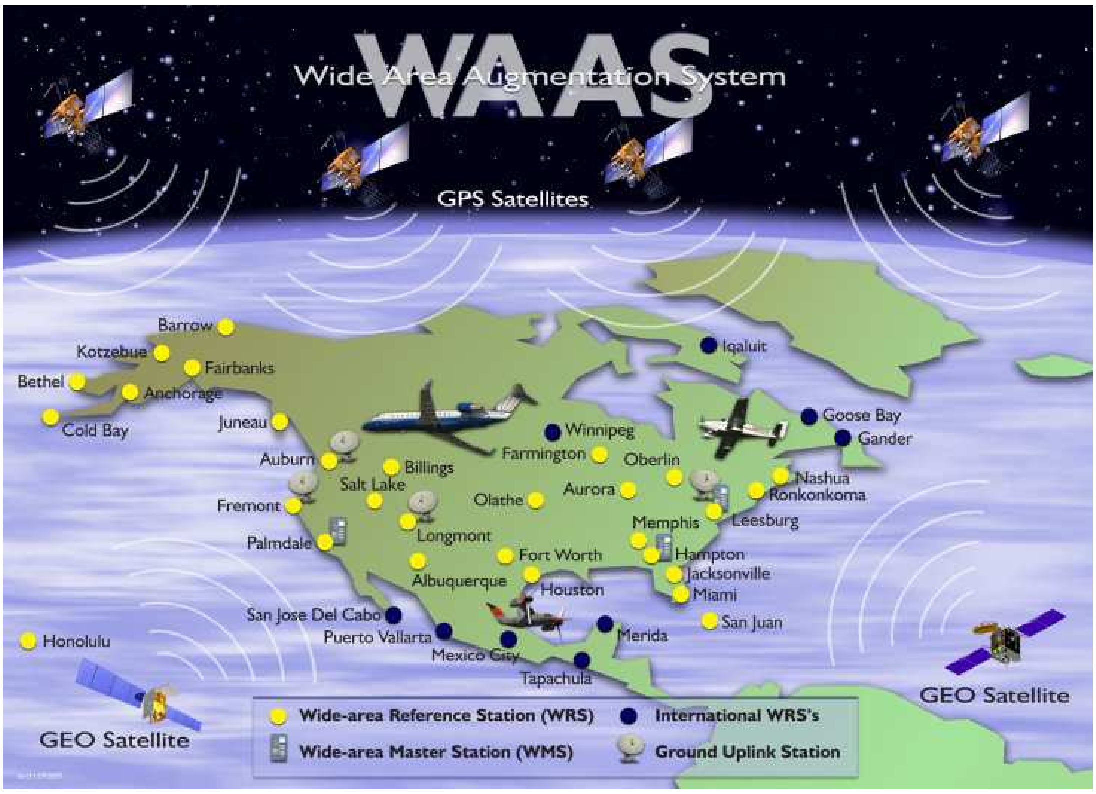

Fig. 2.3 WAAS stations. [6]

The space segment is formed by three geostationary satellites (March 2011), Inmarsat-4 F3, Telesat's Anik F1R and Intelsat's Galaxy 15, located 98º W, 107,3º W and 133º W, respectively.

WAAS specifications require it to provide a position accuracy of 7.6 meters or better at least 95% of time, an error notification of 6.2 seconds maximum, an integrity probability of $1x10^{-7}$ and a continuity probability of 99.999%. However, actual performance has proven better accuracy than one meter laterally and 1.5 meters vertically throughout most part of North America, which make WAAS capable of achieve CAT I requirements. [6]

2.2.2. EGNOS

EGNOS is the SBAS developed by the European Space Agency, the European Commission and Eurocontrol for providing GNSS augmentation services in the European region. It includes working with GPS and GLONASS, but specially with the future European global positioning system, Galileo. The first operational satellites of this system have already been launched in order to validate the system, but it is expected to complete the constellation of thirty Galileo satellites by 2019.

It is formed by 34 Ranging and Integrity Monitoring Stations (RIMS) which pick up GPS signals, four Master Control Centres (MCCs) to process the data delivered by the RIMS, and six uplink stations which send the signal to three geostationary satellites. Those satellites are Inmarsat 3-F2 (15.5º W), Artemis (21.5º E) and Inmarsat 4-F2 (25º E), the latter being used currently to perform tests on the system. [8]

Although initial EGNOS specifications pretended a horizontal position accuracy of less than seven meters and integrity of $1x10^{-7}$, the system nowadays can provide an accuracy position at the meter level. The official start operations started on October 1st 2009 and from March 2nd 2011, EGNOS Safety-of-Life signal was formally declared available to aviation, so EGNOS can support Non-precision Approach and APV.

2.2.3. OTHERS

Other countries and space agencies are also developing other SBAS systems.

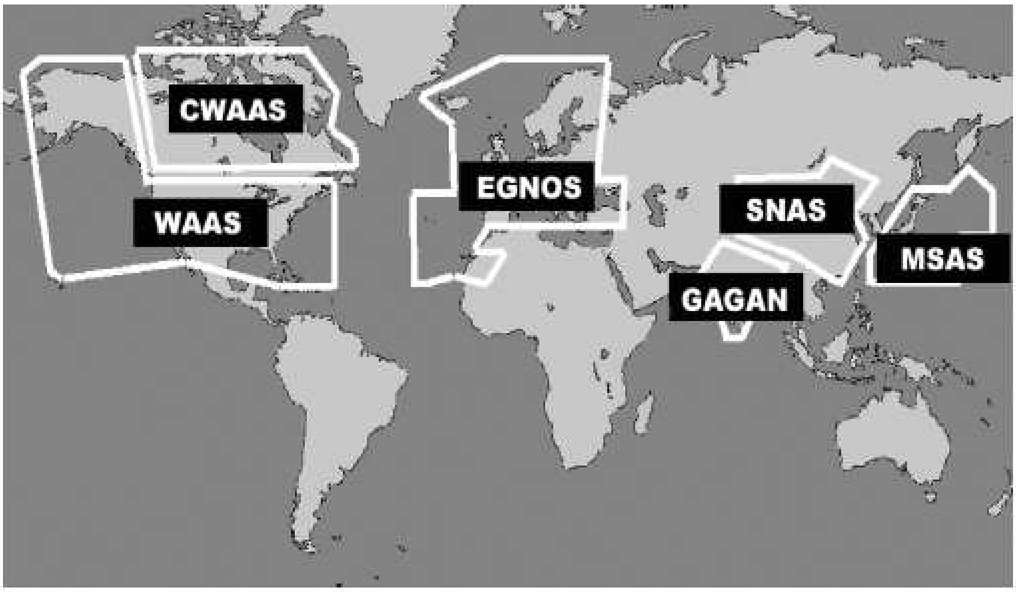

Fig. 2.4 SBAS systems over the world [9].

The Japan Space Agency in collaboration with the Japan Aviation Bureau has developed the MTSAT Satellite-Based Augmentation System (MSAS), which improves the performance of GPS signal in the Asia-Pacific region. It uses two Multifunctional Transport Satellite (MTSAT) geostationary satellites and is interoperable with WAAS [9]. At the present time the system is compliant with the ICAO standards and SARPs for SBAS systems.

GPS and GEP Augmented Navigation System (GAGAN) is the SBAS being developed by the Indian Space Research Organization. It is planned to be into operation by the year 2014. China is also developing a SBAS system, SNAS, which is also in initial phases of development.

2.3. GBAS

2.3.1. Functionality

In contradistinction to SBAS, Ground Based Augmentation Systems use ground stations instead from satellites to transmit the correction signals to the users.

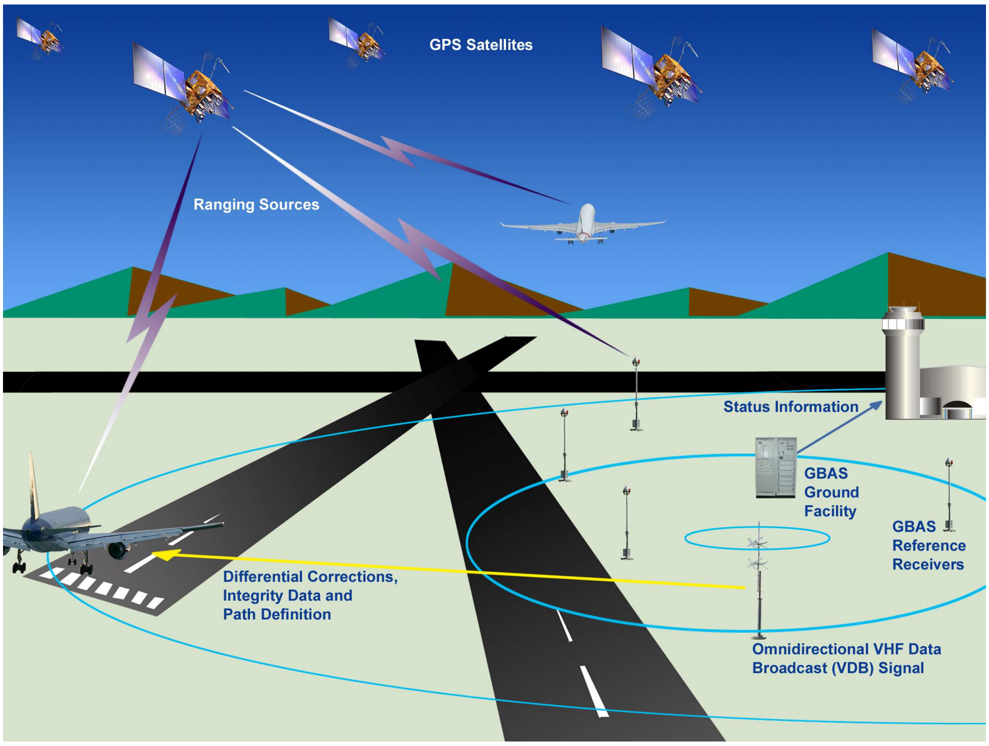

Fig. 2.5 GBAS structure. [10]

The GBAS are formed by three different segments: space segment, ground segment and airborne segment. This topic will be extended in chapter 4.

2.3.1.1 Space segment

In the case of GBAS, the space segment is composed uniquely by the GNSS satellites.

2.3.1.2 Ground subsystem

The ground subsystem is formed by two different kinds of stations, Reference Stations, which are in charge of generating and transmitting the augmentation signal, and Monitoring Stations, which receive the augmentation signal together with the GPS signal and monitor the perform of the system. Reference stations are equipped with a redundant number of GNSS receivers, a data processing station and a VDB station for broadcasting correction and integrity messages.

2.3.1.3 Airborne subsystem

The airborne segment is composed of a GNSS receiver that decodes the satellite signals and a VDB receiver that decodes the correction and integrity messages transmitted by the ground subsystem. With the received data and the attitude information from an inertial reference unit (IRU), a multi-mode receiver calculates ILS-like deviations for input into the autopilot.

The signal transmitted by the reference stations is in the VHF band, between 108 and 117.975 MHz, with channels of 25 KHz, and contains the corrections to satellites' pseudo-range and integrity parameters. The data shall be transmitted as 3-bit symbols, modulated by D8PSK at a rate of 10500 symbols per second.[1]

GBAS can provide flexible and curved approach trajectories and its accuracy can be less than one meter in both horizontal and vertical position so, unlike SBAS, it can provide CAT III approaches. Another advantage of GBAS with respect to ILS or MLS is that a single installation can provide service to all the runways within the coverage area, so the airport facilities can be reduced.

2.3.2. LAAS

Local-Area Augmentation System is GBAS developed by the American Federal Aviation Administration. A LAAS CAT I system has already received the System Design Approval from the FAA and has already been installed in different airports in the US [10]. The performance requirements for LAAS, defined by RTCA are

	HA (95%)	VA (95%)	Integrity Level	HAL	VAL	TTA	Cont.	Avail.
CAT I	16 m	4.4 m	$1\text{-}2x10^{-7}$	40 m	10 m	2 s	$1\text{-}8x10^{-6}$ /15 s	0.99 to 0.99999
CAT II/IIIa	6.9 m /6.2 m	2 m	$1\text{-}10^{-9}$	17.3 m	5.3 m	1 s	$1\text{-}4x10^{-6}$ /15 sec	0,99 to 0,99999
CAT IIIb	6.2 m	2 m	$1\text{-}10^{-9}$	15.5 m	5.3 m	1 s	$1\text{-}2x10^{-6}$ /15 s (lat) $1\text{-}2x10^{-6}$ /30 s (ver)	0,99 to 0,999999

Table 2.2. LAAS performance requirements. [4]

Category	Decision Height (DH)	Runway Visual Range (RVR)
CAT I	≥ 200 ft	>2400 ft
CAT II	100 ft	>1200 ft
CAT IIIa	<100 ft	>700 ft
CAT IIIb	<50 ft	>150 m
CAT IIIc	No DH	No limitations

Table 2.3 DH and RVR for LAAS. [4]

2.3.3. GBAS in Europe

In Europe, Eurocontrol is also developing and testing a GBAS system. GBAS facilities have already been installed in different airports all around Europe, like in Frankfurt and Bremen in Germany or in Malaga airport in Spain, where trials have been taken into account. On February 9th, 2012, the first commercial plane landed using a CAT I GBAS system in Bremen Airport, accomplished by Air Berlin, the first company who has installed GBAS receivers in all its fleet of Boeing-737 [11].

Chapter 3. GNSS errors and local-area corrections generation.

3.1. Sources of error [4]

The different sources of error of GNSS and the capability of augmentation systems to correct them will be discussed in this chapter.

3.1.1. Atmosphere induced errors

There are two different kinds of atmosphere induced errors, the error due to the effect of the ionosphere and the troposphere.

3.1.1.1 Ionospheric effects (I_m^n for the satellite n and the receiver m)

The ionosphere is a region of the atmosphere, which acts as a dispersive medium, located between 70 km and 1000 km above the surface where the ultraviolet rays of the sun ionise molecules of the air releasing free electrons. Those electrons influence the electromagnetic waves of the satellite signal broadcasts causing a delay inversely proportional to the square of the frequency.

In medium latitudes, the ionosphere delay for a satellite in zenith of the receptor varies from 3 to 5 meters during the night up to 5 to 10 meters during the afternoon. In the equator, the delay can reach up to 36 meters in periods of high solar activity [12].

The Klobuchar's model, a set of coefficients transmitted in the navigation message, can reduce this delay in a 50 % for medium latitudes.

3.1.1.2 Tropospheric effects (T_m^n for the satellite n and the receiver m)

The troposphere is the lower part of the atmosphere and even though it is a non-dispersive medium for frequencies up to 15 GHz, it can also produce a delay in the signal. This delay is a function of the tropospheric refractive index, which depends on the temperature, pressure and relative humidity.

The delay error varies between 2 to 25 meters, but can be reduced using different models as Hopfield's, which can reduce it to the 6% of the absolute delay.

3.1.2. Receptor noise and resolution (RN_m^n)

Those errors are produced by the thermal noise in the front-end part of the receiver and can be modelled as white Gaussian noise and are induced by the receiver tracking loops. The order of these errors is few metres for the measure of the code phase and the order of millimetres for carrier phase measurements.

3.1.3. Multipath and shadowing (MP_m^n for ground multipath and DMP_m^n for diffuse multipath)

Multipath is the effect where the signal is reflected or diffracted in different objects as can be the ground, buildings or the plane, so the receptor receives not only the direct path signal, but also delayed rebound signals. The receptor cannot distinguish between the direct and the reflexed signal when they are close in time (the order of tens or hundreds or nanoseconds; it will happen when the reflected signal comes from a nearby objects or from grazing distant objects), so the as the carrier and the phase will be locked with this composed signal, the correlation function with the locally generated signal will be distorted. It also introduces errors in pseudorange and carrier phase measurements from the different satellites, producing errors in position, velocity and time.

The multipath errors can be reduced with an appropriate antenna location, using narrow correlators and choosing the antenna diagram pattern so the gain for low angles will be small.

On the other hand, shadowing is the effect caused by an excess of attenuation of the direct path caused when it propagates through any structure or object. The combination of this effect with a reflected signal can cause the receptor to track only the multipath signals.

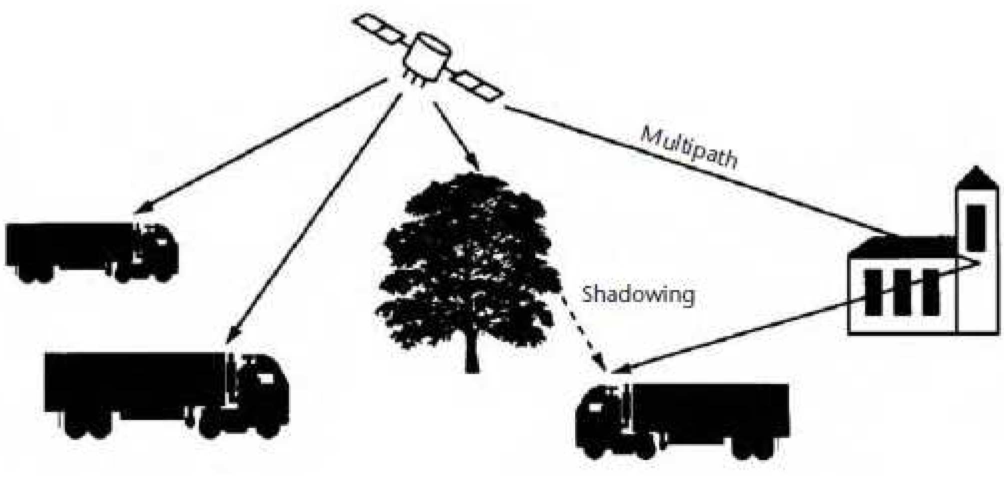

Fig 3.1.. Example of multipath and shadowing

3.1.4. Satellite clock errors (B^n)

Satellite clock errors are caused by the difference between the atomic satellite clock and GPS time that is diffused by the GPS control segment. The navigation message, send from Master Control Stations includes corrections to compensate those clock errors for each one of the satellites. The value of this error is in the order of meters, being minimal after the actualisation of the navigation message and increasing with time until the next reception.

3.1.5. Receiver clock errors (b_m for the receiver m)

This error is produced by the oscillator used in the receiver and it is considered by design as a state of the system so it can be eliminated in the navigation solution.

3.1.6. Errors in ephemeris (dR_m^n for the satellite n)

This error is produced by the difference between the real position of the satellite and the position predicted for it in the ephemeris, which is calculated in the ground stations and send to the satellite, who at the same time re-send the ephemeris to the users.

The value of the error is around 3 meters (1 sigma) in the distance domain and are smaller in the radial component of the orbit and larger in the transversal component due to the fact that all the stations which calculate the orbits are placed in the Earth surface.

3.1.7. Selective Availability

Selective availability consisted in a degradation of the ephemeris of the satellites and a dithering of the satellites clocks caused voluntarily by the US army to degrade the quality of the service for public users. It was deactivated in 2000, what permitted to obtain a much better resolution. The error induced by SA was about 23 meters (1 sigma).

3.1.8. Hardware bias

Hardware bias errors can be produced in satellites as well as in user equipment.

Satellite biases are caused because of the different GPS signals travel through different paths in the satellite in function of its frequency. In dual-frequency users this error is corrected partially with the ionospheric corrections and in mono-frequency receivers it is done with the parameter T_{GD} of the navigation message. The order of the error is about 8 nanoseconds.

User equipment bias errors are small compared with other error sources. They are caused by the delay experienced by the signal as it travels through the radio frequency front end part of the receiver and the digital processing until the carrier-phase measurements are physically made within the digital receiver channels.

3.1.9. Relativistic effects

Relativistic effects have to be corrected in the GPS signal in order to avoid errors which can be considerably sizable.

The special theory of relativity, which shall be considered when the emitter and the receptor of a electromagnetic signal are moving with respect to the frame system, and the general theory of relativity, which shall be considered when the emitter and the receiver are placed in points where the gravitational potential is different. Those effects are corrected adjusting the satellite clock frequency up to 10.22999999543 MHz, so a receiver at sea level obtains the desired frequency of 10.23 MHz [2].

The Earth gravitational field also produces a bent in the space-time which introduces error of 2 cm in absolute positioning and 0.001 ppm in relative positioning.

Another correction shall be induced due to the shape of the orbit of the satellite, which is elliptic. When the satellite is placed in the perigee, its speed is bigger and the potential lower, so the satellite clock is lightly delayed. The opposite effect takes place in the apogee. The maximum error due to this effect could be 70 nanoseconds, which in distance is equivalent to 21 meters.

The last relativistic effect which affects GPS signals is the Sagnac effect. It is produced by the change in the position of the receiver since the time when the satellite transmitted the signal until the time when receives it caused by the rotation of the Earth. Uncorrected could generate an error bigger than 30 meters.

3.2 Corrections generation [12]

The measurement of the pseudorange between the satellite n and the reference receiver m can be expressed as:

$$\rho_m^n = R_m^n + dR_m^n + b_m - B^n + I^n + T^n + MP_m^n + DMP_m^n + RN_m^n \qquad \textbf{(3.1)}$$

Where R_m^n is the distance between the reference receiver m to the satellite n and the rest are the errors mentioned before.

These sources of error can be classified in two groups in accordance with the level of similarity between the measurements of the ground station and the measurements of the user.

In the first group we can find the errors which are not correlated between both measurements, what means that these errors are caused by local perturbations of the signal, or are related with errors of the ground receiver. The errors that can be included in this group are multipath and receiver noise errors.

$$\varepsilon_m^n = MP_m^n + DMP_m^n + RN_m^n \tag{3.2}$$

The second group include the errors which are correlated between the reference receivers and the users and are caused by the spatial segment.

$$PRC_m^n = dR_m^n - B^n + I_m^n + T_m^n \tag{3.3}$$

The effect of PRC are negligible because these errors are cancelled for users which are close to the reference ground receivers.

As the position of the antenna reference receiver is known with high precision and the position of the satellite is also known thanks to the navigation message, the term R_m^n can be obtain accurately, so a estimation of the error in the pseudorange measurements can be expressed as

$$e_m^n = \rho_m^n - R_m^n = b_m + PRC_m^n + \varepsilon_m^n \tag{3.4}$$

What could be send to the user as a differential correction.

It is not useful to send the reference receiver clock error (b_m) in the corrections because it would cause a change in the user's receiver clock error, but it is possible to reduce its size averaging the pseudorange corrections of all the satellites in sight to all the reference receivers. Eliminating this clock error, we obtain the next pseudorange corrections

$$e_m^n - b_m = PRC_m^n + \varepsilon_m^n - PRC_m^{N_1} - \varepsilon_m^{N_1} \tag{3.5}$$

where N_1 indicates the number of common satellites to all the reference receivers and

$$PRC_m^{N_1} = \frac{1}{N_1}\sum_{n=1}^{N_1} PRC_m^n \quad (3.6)$$

$$\varepsilon_m^{N_1} = \frac{1}{N_1}\sum_{n=1}^{N_1} \varepsilon_m^n \quad (3.7)$$

Another procedure to generate more accurate corrections consists in average these corrections between a set of reference receivers, so we obtain the final correction:

$$e^n = \frac{1}{M[n]}\sum_{n=1}^{M[n]} PRC_m^n + \frac{1}{M[n]}\sum_{n=1}^{M[n]} \varepsilon_m^n - \frac{1}{M[n]}\sum_{n=1}^{M[n]} PRC_m^{N_1} - \frac{1}{M[n]}\sum_{n=1}^{M[n]} \varepsilon_m^{N_1} \quad (3.8)$$

where $M[n]$ is the number of reference receivers used for creating the correction and for the satellite n.

The first term represents the real correction and includes the errors correlated between the receivers in a local area while the second represents the error in the pesudorange correction. The third term is equal for all the satellites assuming that PRC_m is practically the same for reference receivers placed nearby, so:

$$\frac{1}{M[n]}\sum_{n=1}^{M[n]} PRC_m^{N_1} = \frac{1}{N_1}\sum_{n=1}^{N_1} PRC_m^n \quad (3.9)$$

The last term depends on the number of reference receivers used in the calculus of the pseudorange corrections for a given satellite. If all the satellites would use M reference receivers, this term would be the same for all the satellites so it would not induce any error in the position, only an apparent change in the user clock bias.

Chapter 4. Architecture of GBAS

4.1. User receiver structure

The on board subsystem of the GBAS system is composed by three elements; a Multi-Mode Receiver (MMR), an Inertial Reference Unit (IRU) and the autopilot.

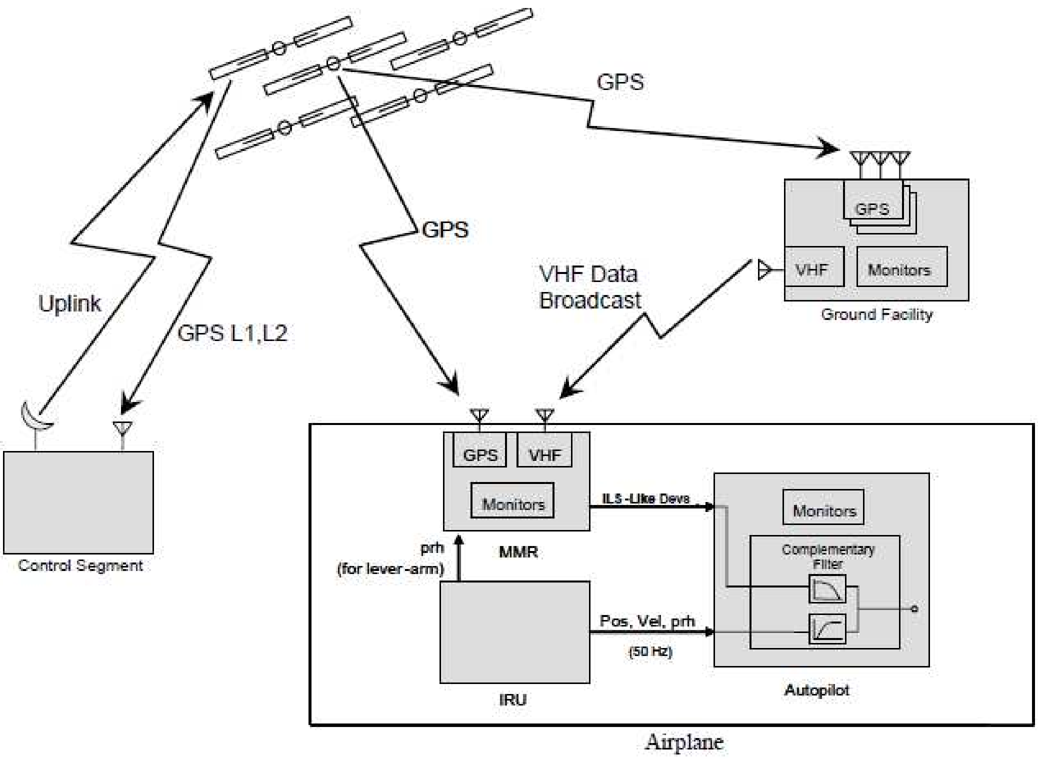

Fig. 4.1 GBAS overall structure. [13]

4.1.1. Multi-Mode Receiver

The function of the MMR is to receive both the GPS signal and the correction signals transmitted via VDB and, along with the attitude information provided by the IRU, calculate ILS-like deviations for input into the autopilot. The design of the VHF receiver will be discussed in chapter 6. The MMR also contains monitoring that compares the calculated protection levels with alert limits.

The GBAS performance model represents the deviation outputs of the MMR. Figure 4.2 represents a block diagram of this performance model.

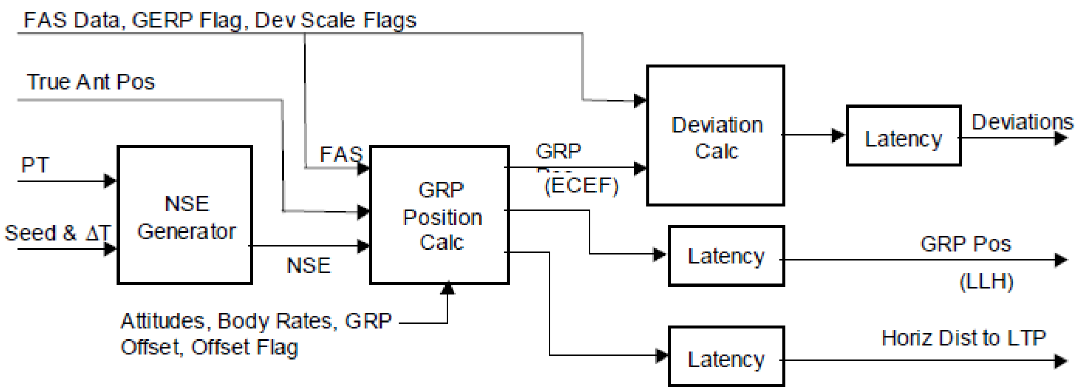

Fig.4.2 GBAS performance model block diagram [13]

First of all, the Navigation System Error (NSE) generator produces vertical, along-track and cross-track NSE, creating a representative output of the GBAS as defined by the requirements imposed by ICAO and RTCA. After this, the GBAS Landing System Reference Point (GRP) Position Calculator adds the NSE to the true position of the airplane, producing the measured position of the GLS Reference Point.

The Deviation Calculator computes the deviations of the GRP given the final approach segment (FAS) data. Finally, a latency model is applied to each output of the GLS model. Those outputs are the GRP position and the horizontal distance to the Landing Threshold Point (LTP).

4.1.2. Inertial Reference Unit

The Inertial Reference Unit is a type of inertial sensor which provides information such as rotational attitude (angular orientation relative to some reference frame) and translational position (typically latitude, longitude and altitude) over a period of time using gyroscopes and accelerometers. With an Air Data Inertial Reference Unit (ADIRU) other information such as airspeed, Mach and angle of attack are also obtain.

As said before, this information is used as inputs both for the MMR as for the autopilot.

4.1.3. Autopilot

Finally, the autopilot combines the measurements from the MMR and the IRU using a complementary filter and uses them for navigation. Autopilot also monitors for anomalous deviation signals.

4.2. Reference station structure

4.2.1. Reference Receiver Subsystem

The Reference Receiver Subsystem consists of a minimum of four Reference Receiver Stations (RRS) each one containing a Reference Receiver (RR) and a Reference Receiver Antenna (RRA). It is responsible for providing typically four pseudorange measurements for each GPS satellite and also provides basic health status of each satellite. The RRA is a Multipath Limiting Antenna (MLA), designed to minimize GPS signal reflections that may cause measurement errors.

The RRS provides a weatherproof enclosure to protect the RR and is mounted in close proximity to the RRA. It also contains the power supply and lightning protection circuits

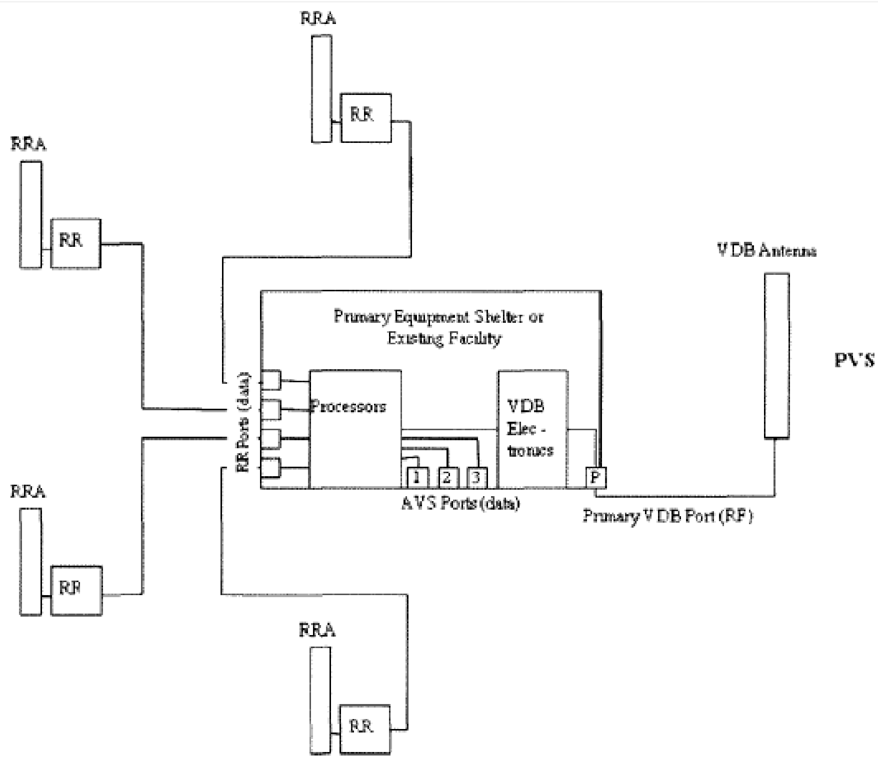

Fig. 4.3. Standard equipment configuration [14]

4.2.2. Processor Subsystem

The Processor Subsystem receives the signal form the RRS and is in charge of performing the correction computations, integrity processes and message generation functions. It is also responsible for critical safety and integrity monitoring of both incoming pseudorange and satellite status and outgoing correction data.

4.2.3. VHF Data Broadcast Subsystem

It is formed by a VDB Antenna and VDB Electronic Equipment. The antenna is a VHF antenna designed to reduce the gain pattern in the direction of the ground plane in order to minimize multipath and shall be located in line-of-sight to all the approaches it is serving.

The Electronic Equipment must be fully redundant and consists of two VHF transmitters and two VDB monitor receivers.

4.2.4. Operations and Maintenance Subsystem

The Operations and Maintenance Subsystem includes the following equipment. A Local Status Panel (LSP) provides visual (LEDs) and audible indicators of the system status, such as the system mode and fault conditions.

A Maintenance Data Panel (MDT), which is typical a laptop computer located in the GBAS equipment rack, is responsible for providing an interference to operators and maintainers of the GBAS Ground Facility.

The Air Traffic Status Unit (ATSU) provides an interface between the system and air traffic controllers, showing them only the status of the system (there are no provisions for ATC to control the GBAS).

Chapter 5. Correction signal characteristics

5.1. Frequency band and modulation

The frequencies selected for GBAS will be inside the band of 108 to 117,975 MHz. The minimum assignable frequency will be 108,025 MHz and the maximum will be 117,950 MHz. The separation between the assignable frequencies will be 25 KHz. [1]

The data shall be transmitted as 3-bit symbols at a rate of 10.500 symbols per second and the modulation in use will be D8PSK. In a differential modulation the phase encoding of the carrier is such that each symbol is represented by the difference between the previous phase and the current phase. This is because the receiver has no phase reference for the carrier signal, so the receiver does not know what the signal should look like with a phase shift of 0 radians. Instead, the receiver can measure the difference between two phases and use this to determine the symbol being transmitted. 8-Phase shift keying means that each transmitted symbol represents one of each eight phase change states of the carrier of 0, $\pi/4$, $\pi/2$, etc. as can be seen in the picture.

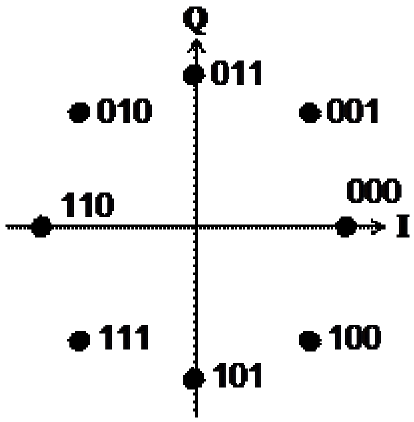

Fig. 5.1 D8PSK modulation scheme

5.2. Message format

The channel access method in use for transmitting the GBAS VDB signal is TDMA. This technique allows several users to share the same frequency channel by dividing the signal into different time slots. The timing structure is based on frames and time slots, where each frame of 500 milliseconds of duration is formed by eight individual time slots (A to H) of 62.5 milliseconds.[1][15]

Each of these time slots shall contain at most one burst, whose length may be variable up to a maximum of 1914 bits. Burst data content is specified in the next table.

Element	Number of bits
Beginning of burst	15 (all zeros)
Synchronization and ambiguity resolution	48
Scrambled data	
Station Slot Identifier	3
Transmission length	17
Training sequence FEC	5
Application data	Up to 1776
Application FEC	48
Fill bits	0 to 2

Table 5.1 Burst data content. [1]

The beginning of the burst is formed by a sequence of 15 zeros followed by another predetermined 48-bit sequence in charge of maintain synchronization and ambiguity resolution. Next are placed the scrambled data content starting with the SSID, which is a numeric value corresponding to the letter designation of the first time slot assigned to GBAS subsystem. Transmission length indicates the total number of bits in both application data and application FEC (Forward Error Correction) while the training sequence FEC is a sequence of 5 bits computed over the SSIC and the transmission length fields using the formulas given by ICAO; the same occurs for the application FEC.

Application data consists of one or more message blocks, containing a message block header of 48 bits, the message itself with up to 1696 bits and a Cyclic Redundancy Check (CRC) of 32 bits. All the message types are:

Message type identifier	Message name
1	Pseudo-range corrections
2	GBAS-related data
3	Null message
4	Final approach segment data
5	Predicted ranging source availability
6	Reserved for future CATII/III
7	Reserved for national applications
8	Reserved for test applications
11	Pseudo-range corrections-30 second smoothed pseudoranges
101	GRAS pseudo-range corrections

Table 5.2 GBAS VHF data broadcast messages [15]

Type 1 message, as defined by ICAO, provides the differential correction data for the GNSS ranging sources. It also contains information like ephemeris decorrelation parameter or satellite availability and information about the message itself, like the time of validity.

Type 2 messages identify the location of the GBAS reference point at which the corrections provided apply and give other related data like the number of reference receivers of the ground station or the accuracy level.

Type 3 message is a variable length “Null message” which is intended to be used by ground subsystems that support authentication protocols.

Type 4 message contains one or more sets of FAS data, each defining a single approach. The FAS path is the line in space defined by the landing/fictitious threshold point, the flight path alignment point, the threshold crossing height and the glide path angle.

Type 5 messages contain information for the currently visible or soon to be visible ranging sources while type 11 provides the same information as type 1 but with a 30 second code-carrier smoothing applied.

5.3. Field strength

ICAO also defines the field strength that required in the GBAS coverage area, which are summarized in this table.

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Minimum field strength</td><td colspan="2">Maximum field strength</td></tr>
<tr><td>V/m</td><td>dBW/m²</td><td>V/m</td><td>dBW/m²</td></tr>
<tr><td colspan="2">Horizontally polarized signal</td><td>0.000215</td><td>-99</td><td>0.35</td><td>-35</td></tr>
<tr><td rowspan="2">Elliptically polarized signal</td><td>Horizontal component</td><td>0.000215</td><td>-99</td><td>0.35</td><td>-35</td></tr>
<tr><td>Vertical component</td><td>0.000136</td><td>-103</td><td>0.221</td><td>-39</td></tr>
</table>

Table 5.3. Minimum and maximum field strength within the GBAS coverage area. [1]

This coverage area for a CAT I precision approach is fixed by the next defined delimitations [1]:

- Laterally begins at 140 m (450 ft) each side of the Landing Threshold Point (LTP) or Fictitious Threshold Point (FTP) and projecting out ± 35º either side of the final approach path to a distance of 28 km (15 NM) from the LTP/FTP and ± 10º either side of the final approach path to 37 km (20 NM)

- Vertically, within the lateral region, up to greater of 7º or 1.75 promulgated glide path angle (GPA) above the horizontal with an origin at the glide path interception point (GPIP) and 0.45 GPA above the horizontal or such lower angle, down to 0.30 GPA, as required, to safeguard the promulgated glide path intercept procedure. This coverage applies between 30 m (100 ft) and 3000 m (10.000 ft) HAT.

Even though these delimitations, the GBAS corrections signals should be transmitted omnidirectionally in order to support future applications.

Chapter 6. GBAS VHF Data Broadcast receiver

In this second part of the project, the design of the radio frequency front-end of the GBAS airborne avionics will be done.

As it was explained in the previous chapters, the network of ground stations of the GBAS systems transmits the corrections made to the GPS system to all the users with the respective receiver. These corrections are transmitted via VDB in the frequency band between 108 and 117,975 MHz with a channel separation of 25 KHz and the modulation in use is D8PSK.

With these requirements, the on-board receiver should follow the scheme of a super-heterodyne receiver, with the following block-diagram.

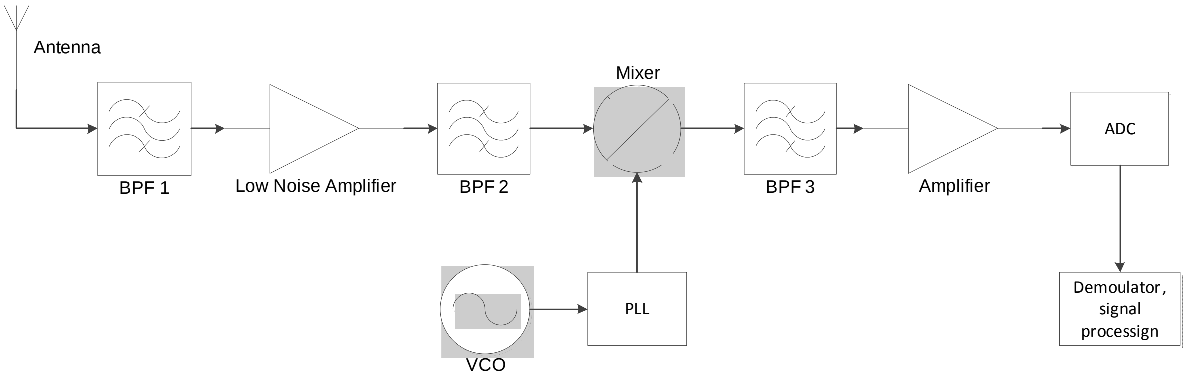

Fig. 6.1 Block diagram of the receiver

A brief description of each block is made below.

6.1. Antenna

The antenna shall be able to receive the signal in the frequency band required. The DM N4-4 antenna model, designed by *Dallas avionics*, fulfils this requirement as its frequency range is from 108 MHz up to122 MHz.

Fig. 6.2 DM C50 VHF Antenna model. [16]

This antenna, consisting of two centered-fed half-loops and a cable harness, has a gain of 0 ± 2 dBi and an impedance of 50 Ω. The polarization is only horizontal and the radiation pattern is omnidirectional in the azimuth plane and approximately cos ∅ in the vertical plane.

Even though in the previous chapter we saw that ICAO defines the field strength for horizontal and elliptical polarized signals, we will assume that our signal is just transmitted horizontally polarized.

6.1.1. Signal power

With the field strength values of the preceding chapter and the characteristics of the antenna we can calculate the signal power levels which will be find in the output of the antenna and the input port of the first filter with the next formula:

$$P_r = W_{inc} \cdot A_e = W_{inc} \cdot \frac{G \cdot \lambda^2}{4\pi} \quad \textbf{(6.1)}$$

where:

P_r = power delivered to the load [W]
W_{inc} = field strength [W/m^2]
A_e = partial effective antenna area [m^2]
G = antenna gain
$\lambda = \frac{c}{f_c}$ = wavelength [m]
f_c = operating frequency [Hz]

With the strength field values delivered to the load given by ICAO, we calculate the minimum and the maximum power level in order to obtain the range in which our receiver has to be able to work, using in both cases a center frequency of 113 MHz.

To obtain the minimum power level, the gain is set to –2 dB and for obtaining the maximum to 2 dB. The values obtained are, for a horizontally polarized signal, a minimum power of $4.45 \cdot 10^{-11}$ W (-103.5 dBW) and a maximum signal power of $2.81 \cdot 10^{-4}$ (-35.5 dBW).

The insertion losses produced in the cables of all the receiver have not been taken into account.

6.1.2. Noise power

The antenna will also receive a noise signal which will interfere with the corrections signal. This noise will be white and gaussian, which means that it is uncorrelated in time and its probability density function is equal to that of the normal distribution.

The power of this noise can be calculated using the next formula

$$P_n=K\cdot T_e\cdot B \qquad \textbf{(6.2)}$$

where

K= Boltzman's constant= $1.38\cdot10^{-23}$ [J/K]
T_e= equivalent noise temperature [K]
B= bandwidth [Hz]

In our case, as the receiver's antenna is pointing to ground, the equivalent noise temperature varies with parameters such as the physical temperature or the terrain, but it can be fixed as 290 K, which is a reasonable value for most of the cases. The value obtained for the noise power is $4\text{x}10^{-17}$ W (-164 dBm). [17]

6.2. Band pass filter 1

The function of this first filter is to select the band between 108 and 117,975 MHZ and to eliminate all the other signals which are not in this band.

The filter designed is a band pass filter using LC components. There are two topologies that are used for these filters, namely the Pi and the T configurations, which, rather than having a single element in each leg of the filter as in the case of low pass and high pass filters, the band pass filter has a resonant circuit in each leg. These resonant circuits are either series or parallel tuned LC circuits. [18]

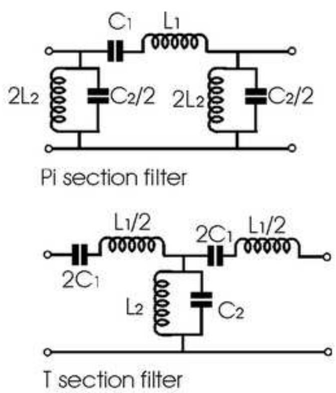

Fig. 6.3 LC Pi and T section band pass filters [18]

To obtain the desired frequency response of the filter, the values of the different capacitors and inductors shall be calculated using the next formulas:

$$L_1 = \frac{Z_0}{\pi \cdot (f_2 - f_1)} = 1.596\,\mu H \qquad \textbf{(6.3)}$$

$$L_2 = \frac{Z_0 \cdot (f_2 - f_1)}{4\pi \cdot f_2 \cdot f_1} = 3.115\,nH \qquad \textbf{(6.4)}$$

$$C_1 = \frac{(f_2 - f_1)}{4\pi \cdot f_2 \cdot f_1 \cdot z_0} = 1.246\,pF \qquad \textbf{(6.5)}$$

$$L_2 = \frac{1}{\pi \cdot z_0 \cdot (f_2 - f_1)} = 0.637\,nF \qquad \textbf{(6.6)}$$

where z_0 is the characteristic impedance (50 ohms in our case) and f_1 and f_2 are the filter cut off frequencies (108 MHz and 117.975 MHz respectively).

With the help of the software Advanced Designed System we can make a simulation of this filter to check the suitability of the calculated components. The configuration chosen for the simulation is in T, but there are no differences in the response when the component values are fixed for each case. The obtained plot shows the attenuation in dB with respect to the frequency.

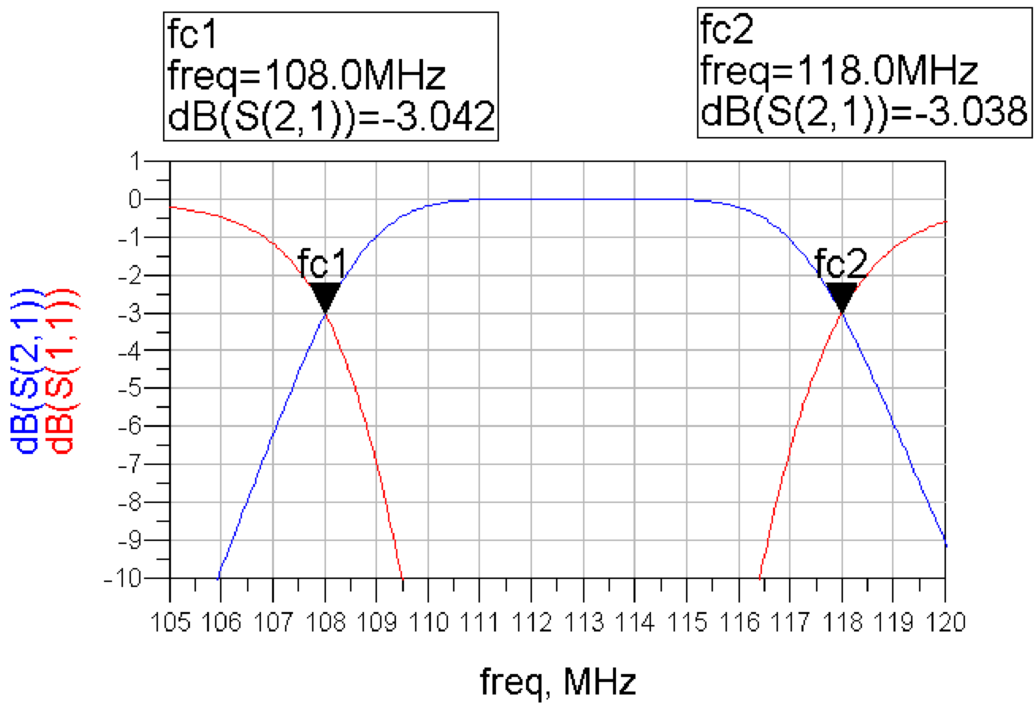

Fig. 6.4 Band pass filter response.

It can be seen that the cut off frequencies correspond with an attenuation of 3 dB, the desired value.

The simulation of the filter has been made using the exact values calculated theoretically. The selection of commercial values as well as a tolerance study is left for a future study if necessary.

6.3. Low Noise Amplifier

The function of the low noise amplifier is to amplify very weak signals that were received by the antenna. The position of this element should be as close to the antenna as possible in order to minimize the noise figure of the overall receiver. From the Frii's formula it is deduced that the overall noise figure of a receiver's front end is dominated by first stages. Placing the LNA in the appropriate location, we ensure that the effect of noise from the subsequent stages of the receive chain is divided by the gain of the LNA and the low noise of this element is injected directly into the received signal.

In the design of the receiver, a commercial LNA chip has been selected in order to obtain a real reference for the different values such as noise figure and gain, even though the complete design of the system will not be done.

The LNA MAX 2665, built by *Maxim Integrated Products, Inc* was chosen. The characteristics of this amplifier, extracted from the datasheet are suitable for this receiver and are summarized in the next table.

Frequency range	75 MHz to 230 MHz
Noise figure	1,1 dB
Supply voltage	2,4 V to 3,5 V
Supply current	3,3 mA
Power gain	11,8 to 18 dB
Temperature range	-40ºC to +85ºC
Cost per unit (from 1000 units)	0,78 $

Table 6.1 Characteristics of the MAX 2665 [19].

From the graphic below we can find the gain in dBs depending on the frequency for different temperatures for a typical supply voltage of 2,7 V. In our range of frequencies, the gain is very stable and do not varies significantly. For example, at a temperature of 25ºC, the gain will be of 15.1 dB.

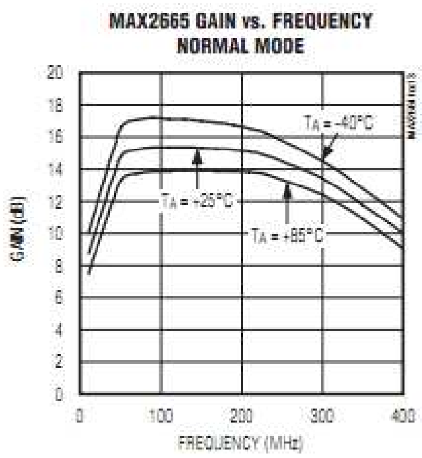

Fig.6.5. Gain in dB as a function of the frequency for the range of temperatures when the supply voltage is 2,7 V. [19]

In the datasheet we can also find the application circuit for the LNA, formed by a inductor L_3 of 33 nH and the capacitors C_3 and C_4 with values of 2200 pF and 1000 pF respectively. [6.1]

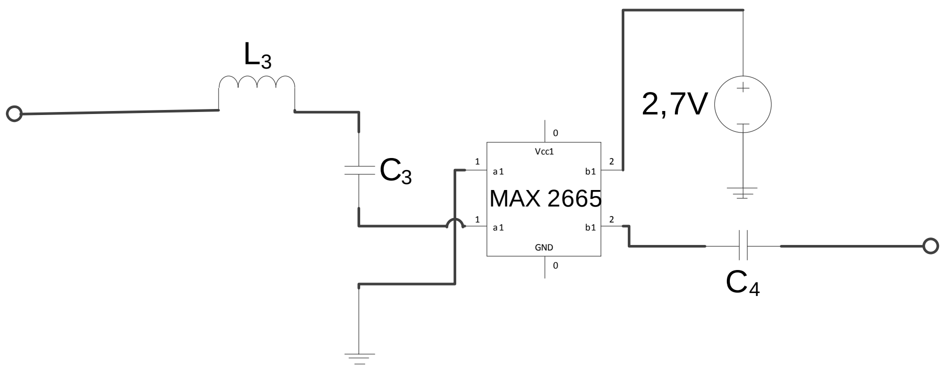

Fig.6.6 LNA application circuit [19]

6.4. Band pass filter 2

This second band pass filter is an exact copy of the first one and its only purpose is to eliminate residual harmonic signals that can be created by the amplifier.

Therefore, at the output port of this filter, the signal is formed by all the channels in our range of frequencies, between 108 MHz and 117,975 MHz. In the next step the signal will be down-converted into the intermediate frequency.

6.5. Mixer

The function of the mixer is to multiply the incoming signal by another one of a different frequency so the signal will be converted into two different frequencies. The lowest one will appear in the difference of the two frequencies and the highest will be in the sum of both. We will be interested in the first one and will filter the rest.

If we represent our input RF signal as $m(t)\cdot cos(\omega_c t)$ and we multiply it by a single frequency component (cos$(\omega_{lo}t))$ we will obtain:

$$m(t)\cdot\cos(\omega_c t)\cdot\cos(\omega_{lo}t)=\frac{1}{2}m(t)\cdot\cos[(\omega_c-\omega_{lo})t]+\frac{1}{2}m(t)\cdot\cos[(\omega_c+\omega_{lo})t] \quad \textbf{(6.7)}$$

where the first component will be our desired component at the intermediate frequency and the second one will be eliminated by filtering.

In this case, the frequency of our incoming signal will be between 108 MHz and 117,975 and the resulting signal should be centered in 10,7 MHz. This intermediate frequency is the most common for FM modulation and here was chosen for the easiness of finding a properly filter in the next step.

Therefore, for making this down-conversion, we need to multiply the incoming frequency by another signal, which will be produced in the PLL. This signal should range between 107,275 MHz and 97,3 MHz. For example, if we select in the PLL the frequency of 107,275, the last channel of the incoming signal, which was centered in 117,975, will appear in the frequency of 10,7 MHz but if, on the other hand, the signal from the PLL has a frequency of 97,3, we will select in the 10,7 MHz band the first channel of the signal, which was in 108 MHz.

The chip that will be used is SA612, manufactured by Phillips Semiconductors. The characteristics of this mixer, extracted from the datasheet [20], are summarized in this table:

Maximum supply voltage	9 V
Supply current (typical)	2,4 mA
Operating temperature range	-40ºC to 85 ºC
Maximum input signal frequency	500 MHz
Maximum oscillator signal frequency	200 MHz
Noise figure at 45 MHz	<6 dB
Minimum signal power	-149 dBW
Minimum signal to noise ratio	12 dB
Conversion gain	17 dB

Table 6.2. SA612 characteristics [20]

Those two last parameters have to be checked in order to see if this mixer is suitable for the receiver. First of all, this table summarizes the characteristics of gain and noise figure of the elements until the mixer. For both band-pass filters we will assume the worst condition, which occurs for the first and the last channels, when the signal is reduced in 3 dB.

	Gain	*Noise Factor*
	dB	dB
BPF1 (1)	-3	3
LNA (2)	15.1	1.1
BPF2 (3)	-3	3

Table 6.3 Elements characteristics summary.

As seen in the table x., the minimum signal power in the entry of the first filter will be –103.5 dBW. Subtracting the losses of the filters and adding the gain of the LNA we obtain a signal of –92.4 dBW, which is considerably bigger than the requires. This restriction of the mixer do not represents any inconvenience for our application.

To calculate the signal-to-noise ratio at this point we need to use the Frii's formula, which relates the noise figure with the signal-to-noise ratio

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} = \frac{S_a / N_a}{S_0 / N_0} \qquad \textbf{(6.8)}$$

where S_a/N_a is the signal-to-noise ratio at the input of the first filter and S_0/N_0 is the signal-to noise ratio at the input of the mixer. With the values from the table 6.3. for the noise figures and gains and the values for the minimum signal power of -103.5 dBW and a noise power of -164 dBW (+ 2 dB which could be added by the antenna in the worst case) we obtain a signal-to-noise ratio before the mixer of 56.25 dB. Like the factor of the minimum signal power, the signal-to-noise ratio do not represents an inconvenient for this element.

The datasheet of the SA612 indicates how it must be connected. The signal will enter in the mixer by the pin 1 INPUT A and will be mixed by the signal coming from the PLL entering by the pin 7. The output signal will be extracted from pin 4. Pin 3 will be connected to ground and the control voltage (pin 8) will be of 6 V.

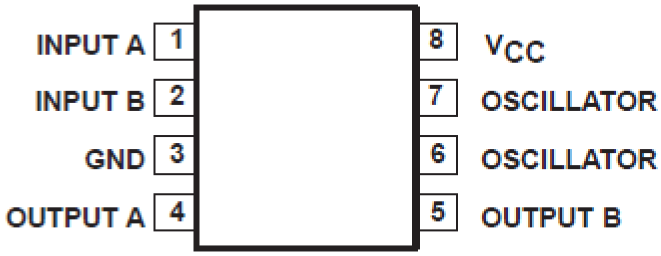

Fig.6.7 Pin configuration of the SA612 [20]

6.5.1. Image frequency

Another effect that shall be considered is the image frequency. The image frequency is an undesired frequency which will produce the same intermediate frequency as the input signal, after being multiplied in the mixer by the local oscillator signal. It can cause interferences in the channel selected so it must be eliminated attenuating this component of the incoming signal with the previous filters.

It can be calculated as:

$$f_{image} = \left| f_s - 2 f_{if} \right| \tag{6.9}$$

where

f_s = input frequency [Hz]
f_{if} = intermediate frequency [Hz]

In our receiver, the input frequency varies between 108 and 117.975 MHz and the intermediate frequency selected is 10.7 MHz. Thus, the image frequency will range between 86.6 MHz for the first channel up to 96.575 MHz for the last one.

The signals in this frequency will suffer an attenuation because of both band-pass filters but will be amplified by the LNA and the mixer itself. Specifically, each one of the filters will produce an attenuation of nearly –33 dB in the case of the image frequency that suffers less losses as can be seen in figure 6.8. The LNA will amplify this frequencies 15.1 dB and the mixer around 17 dB, so in total a signal centered at 96.575 MHz will suffer an attenuation of –33.9 dB.

Also has to be taken into account the fact that the antenna is designed for working in the 108-122 MHz band, so these image frequencies, which do not enter in this band, will suffer additional losses.

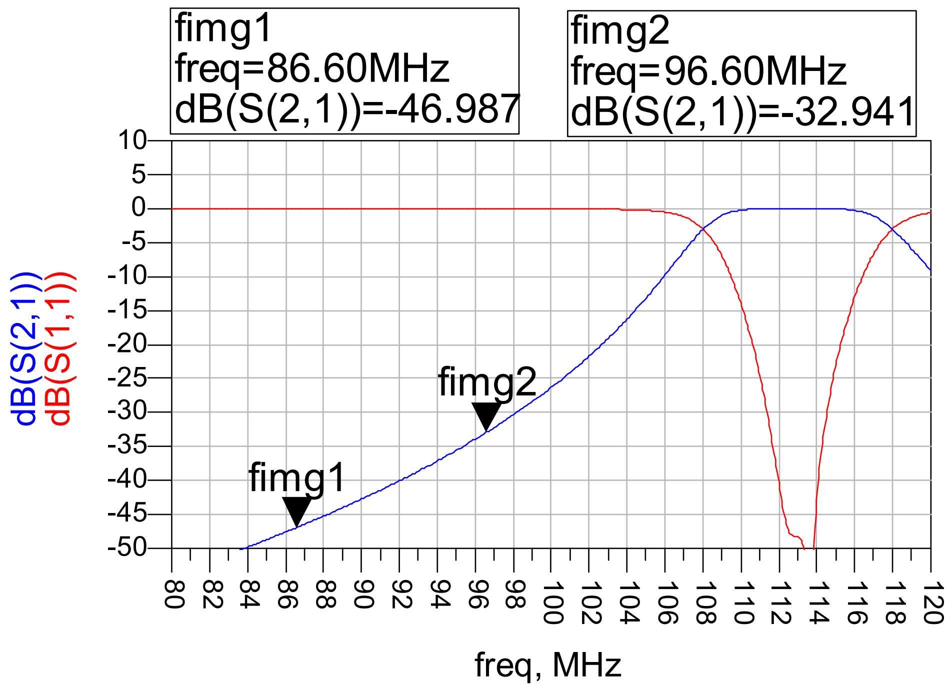

Fig.6.8 Image frequency attenuation in BPF 1 and 2.

6.6. PLL and Voltage Control Oscillator

The function of the PLL (Phase-locked loop) is to generate the signal that will be mixed with the information signal with the objective of making the down-conversion. The phase of this output signal is related to the phase of an input reference signal.

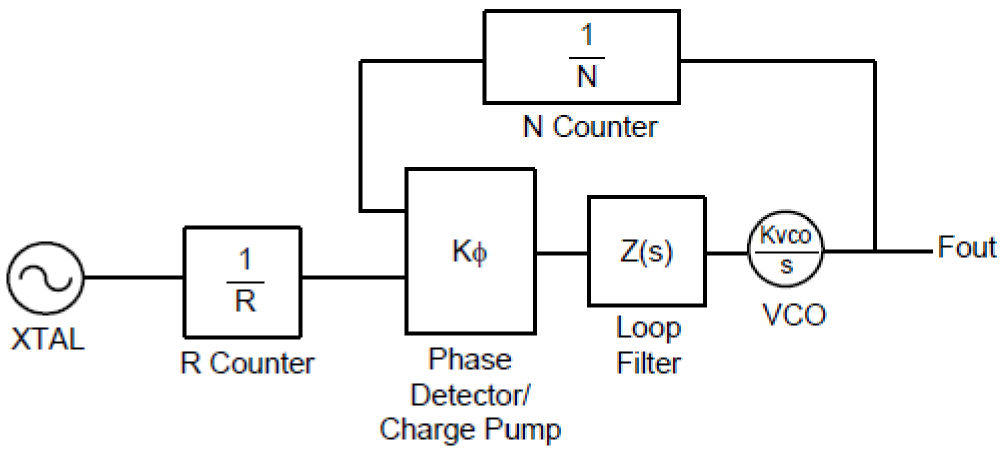

Fig 6.9 Block diagram of the PLL [21]

First of all, a crystal oscillator generates a signal with a very stable frequency, which is then divided by the R counter, so it is produced what is called the comparison frequency. After that, the phase detector compares this signal with the signal derived from the output oscillator and generates an error signal, which is proportional to the difference of frequencies. The error signal is filtered and then used to control a voltage control oscillator, which produces the final output signal (F_{out}).

The output signal is fed through a frequency divider (N counter) back to the input of the phase detector. If this output frequency varies, the error signal will be increased, driving the frequency in the VCO in the opposite direction to reduce the error. Thus, the output is locked to the frequency at the other input, and the signal generated becomes very stable.

As the intermediate frequency is 10,7 MHz, the frequency of the output signal should be 10,7 MHz below the channel that is wanted to select, so F_{out} should range between 97,3 and 107,275 MHz.

If we use a typical fixed crystal oscillator of 10 MHz, and we choose and R value of 400 to yield a comparison frequency of 25 KHz, equal to the channel spacing [6.4], and using the formula:

$$Fout = \frac{N}{R} \cdot XTAL \qquad \textbf{(6.10)}$$

We find that the value of N should vary between 3892 and 4291.

6.7. Band pass filter 3

The purpose of this filter is to select the specific channel and eliminate all the other components of the signal. Due to the fact the channels are only 25 kHz bandwidth, LC filters like the two previous ones are not enough. The filter should have a high Q factor so a ceramic filter has been chosen.

Fig. 6.10. Ceramic filter. The centered pin is connected to ground while the other two are for the input and the output respectively. [22]

The most suitable filter found was SFVLF10M7MF00-B0 manufactured by Murata Electronics North America and with a cost of 1,78 $. [22] This filter is centered at 10,7 MHz and has a bandwidth of 25 kHz, required for selecting the appropriate channel, with a 3dB bandwidth of 50 kHz and insertion losses of 5.5 dB.

The simulation of the filter using ADS and approximating the filter as a Butterworth filter follows:

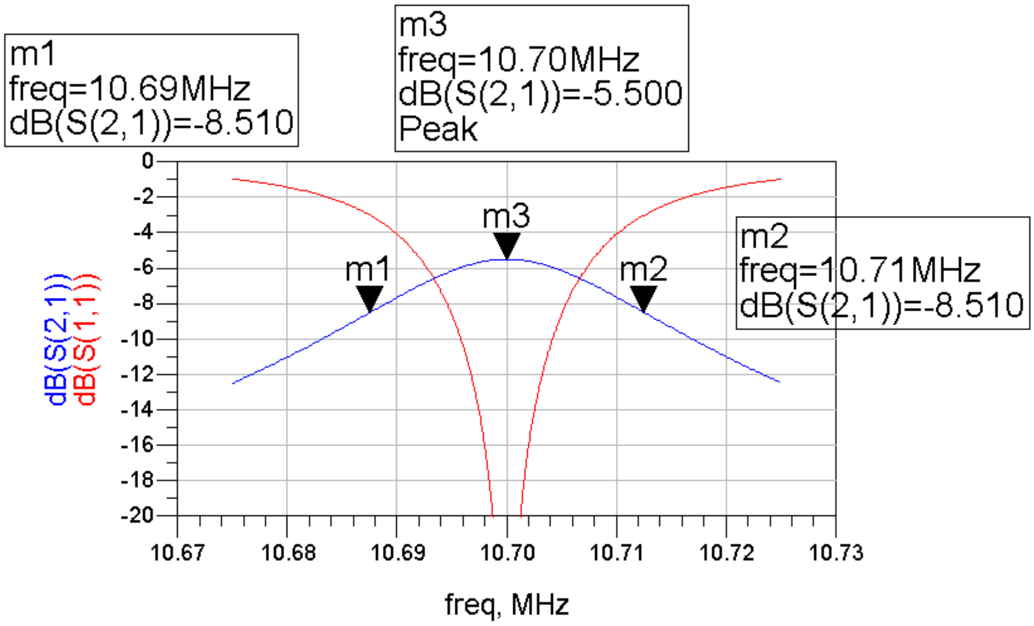

Fig.6.11 Ceramic filter response.

6.8. Output signal

At the output of the third band pass filter, the desired channel has been selected and that is the only information on the signal. That is the output port of the receiver front-end but signals still have to be sampled and demodulated to extract the information. Before being digitalized, the signal should be amplified to match the input level of the ADC.

As a summary of the receiver, are left to calculate the signal power at the exit of the third band pass filter and the noise figure. Next table summarizes the parameters of the different elements.

	Gain	*Noise Factor*
	DB	DB
BPF1 (1)	-3 (first and last channel) 0 (rest of channels)	3
LNA (2)	15.1	1.1
BPF2 (3)	-3 (first and last channel) 0 (rest of channels)	3

MIXER (4)	17	5
BPF3 (5)	-5.5	5.5

Table 6.4. Summary of the characteristics of all the elements of the receiver

To calculate the power range of the signal we will start from the signal levels that the antenna receives, which range from $4.45 \cdot 10^{-11}$ W (-103,5 dBW) to $2.81 \cdot 10^{-4}$ W (-35.5 dBW). The maximum power at the end of the receiver's front end part will correspond to a centered channel, so the two first filters will not add any losses. After the calculation, we obtain a value of 0.128 W (-8.9 dBW).

The minimum power signal will be in the first or the last channel, when the filters add a 3 dB loss each. The value will be $5.05 \cdot 10^{-9}$ W (-82.9 dBW)

On the other side, the noise figure of the complete receiver can be calculated using the Frii's formula, giving a value of 4.65 dB. The signal-to-noise ratio at the end of the receiver will be then 55.82 dB.

Chapter 7 Receiver front end simulation

The simulation of the design made in the previous chapter will be done using the software Advanced Design System. ADS is an electronic design automation software system produced by Agilent Eesof EDA, a unit of Agilent technologies, which provides an integrated design environment for simulating radio frequency electronic products such as radar systems, satellite communications, wireless networks, etc. [23]

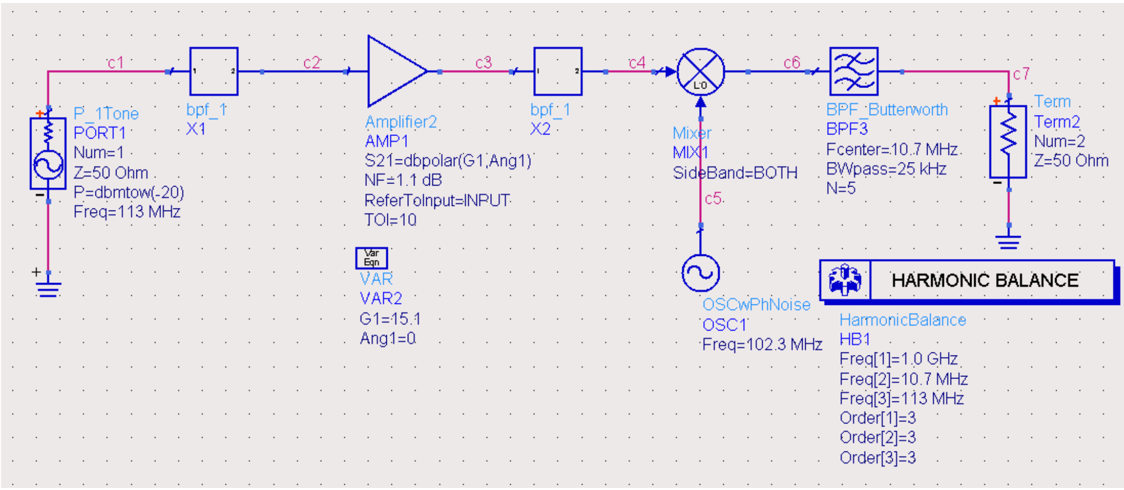

Fig.7.1 Receiver simulation on ADS

The figure above represents the complete simulation of the receiver front end with all the blocks. The simulation has been done using harmonic balance simulation in contradistinction with the simulation of the filters, which use S-parameters simulation. Harmonic balance is a highly accurate frequency-domain analysis technique for obtaining the steady state solution of nonlinear circuits and systems. It is the method of choice for simulating analog RF and microwave problems that are handled in the frequency domain. [24]

7.1. Received signal and BPF1

First of all, the input signal is generated. The simulation will be done simulating the input signal as a tone centered in the frequency of the channel with a determined power. As an example the channel at 113 MHz will be chosen with a power of –20 dBm, a value which is inside the received power range fixed by ICAO.

The first block that the signal will find will be the BPF1. The signal of 113 MHz (m2) will not suffer any attenuation at this point, as seen in the previous chapter, but a signal (m1) placed in the first (or the last) channel will reduce its power in 3 dB as can be seen on fig.7.2.

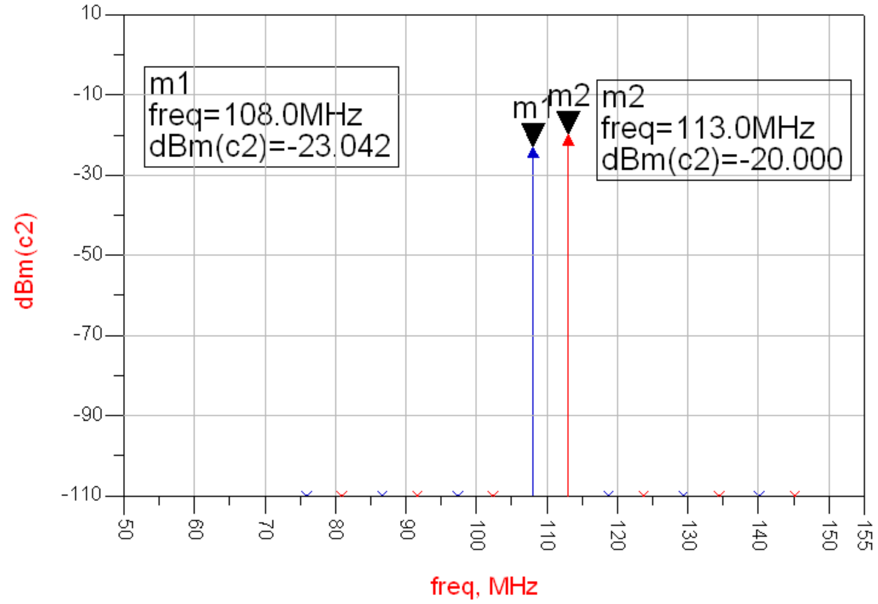

Fig.7.2 Signal after BPF1

7.2. Low Noise Amplifier

The LNA will amplify the signal 15.1 dB at any frequency, so the 113MHz signal (m3) will have a power of –4.9 dBm.

All the amplifiers produce another kind of effect to signals apart from amplification, what is known as harmonic distortion. The harmonics of a signal are signals which are related with the original with an integer factor. These signals may appear at a much lower power level and usually odd harmonics are more powerful than pair harmonics.

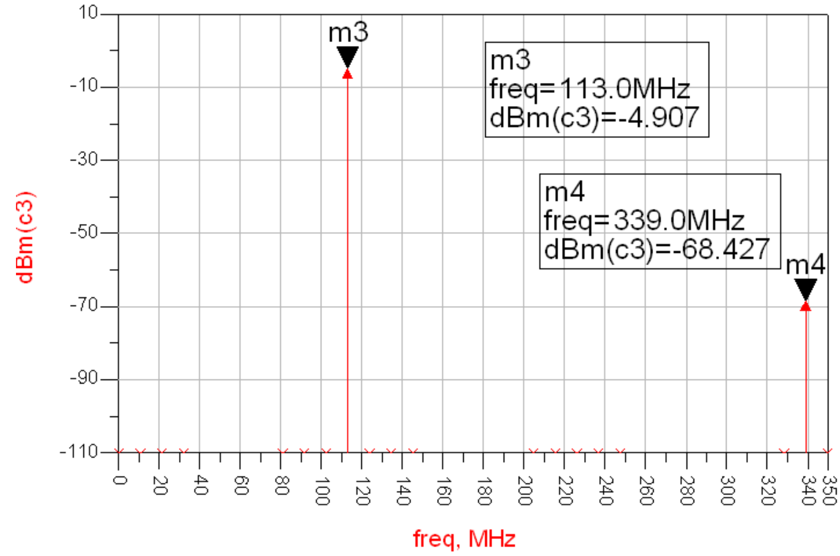

Fig.7.3 Signal after the LNA

In our case, it can be observed that the LNA has produced an harmonic at 339 MHz (m4), which is exactly three times the input frequency. This harmonic has a power of –68.4 dB an has to be eliminate in order to not to cause any undesired effect in the mixer.

7.3. Band-Pass Filter 2

This filter has the function mentioned before of eliminate the harmonic signals and reduce its power so they will not interfere with the local oscillator frequency to produce an undesired signal. Furthermore, it will help to reduce the power of an image frequency which would fall at 10.7 MHz after mixing.

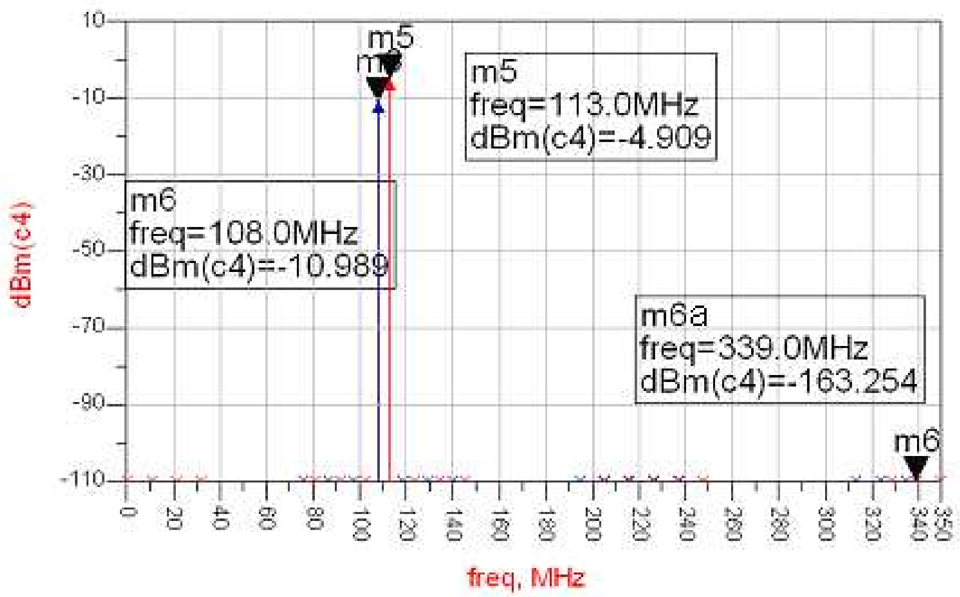

Fig.7.4 Signal after BPF2

The harmonic signal (m6a) has been reduced its power to –163 dBm, while the input signal at 113 MHz (m5) continues with the same power level. As in the first filter, the first (m6) and the last channel suffer an attenuation of 3 dB, so at this point the difference between a centered channel and on of these is 6 dB.

7.4. Frequency synthesizer signal

The simulation of the PLL and the VCO could not be taken into account, so for creating the signal that will be mixed with the input signal, a local oscillator is used, which can provide a tone at the desired frequency. The frequency range varies from 97.3 MHz up to 107.275 MHz and for example input of 113 MHz it corresponds a signal of 102.3 MHz (m7), with a power of 0 dBm.

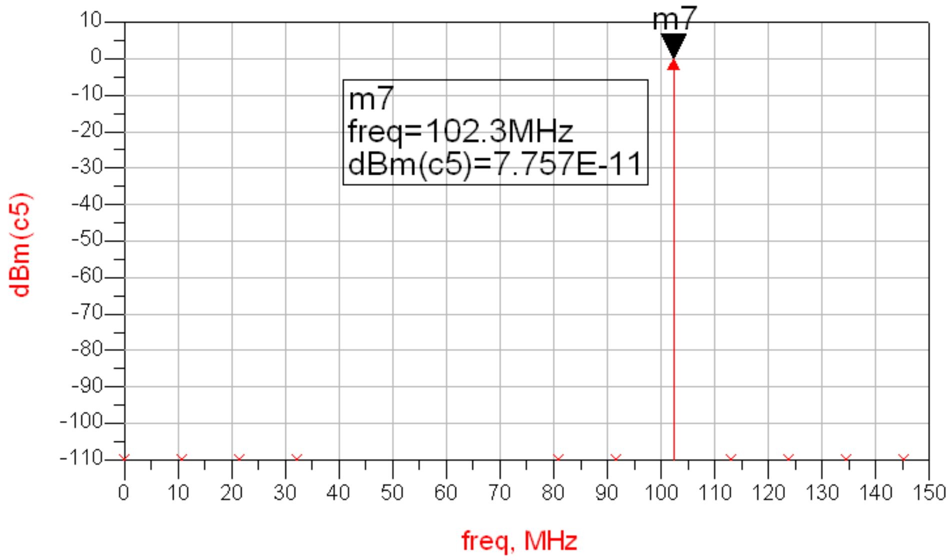

Fig.7.5 Signal from the local oscillator

7.5. After the mixer

Once both signals have been mixed, we obtain our channel (m8) lowered to the desired frequency of 10.7 MHz. In addition, the tone of the sum of the local oscillator and the intermediate frequency (m9) also appears and will be eliminated in BPF3.The third tone (m10) that appears in figure 7.6 corresponds to the harmonic at 339 MHz mentioned before lowered 102.3 MHz. Its power is too low to consider that it may cause any problem.

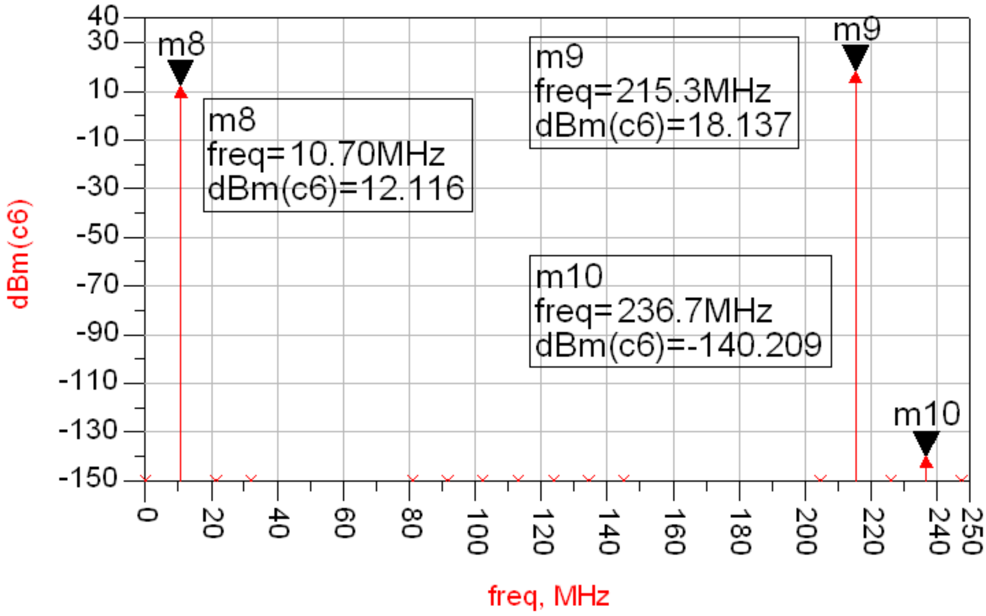

Fig.7.6 Signal after the mixer

7.6. Final signal

The last block that the signal has to pass is the ceramic filter. Here, the channel centered at 10.7 MHz will suffer an attenuation of 5.5 dB due to the filter's insertion losses.

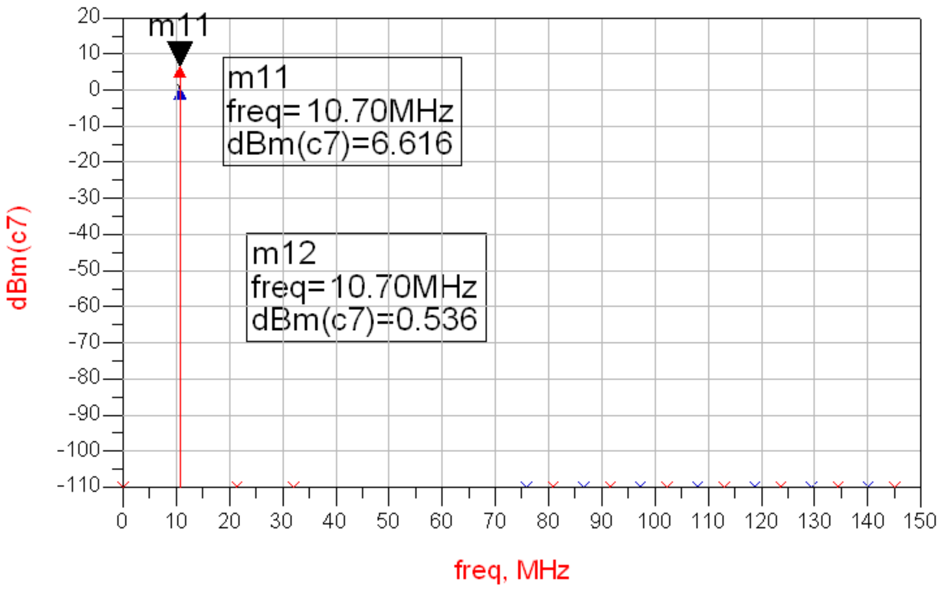

Fig.7.7 Output signal of the receiver front end

At the output of the filter, the only signal present is the desired channel at 10.7 MHz. The power for the 116 MHz (m11) is around 6.6 dBm ($4.57 \cdot 10^{-3}$ W) for an entry signal of –20 dBm. For the first ant the last channels (m12), the power is 6 dB lower, exactly 0.5 dBm ($1.13 \cdot 10^{-3}$ W). The power of the centered channel has been increased in 26.6 dB while the first channel has increased 20.5 dBm. The values correspond with the ones calculated in the previous chapter.

CONCLUSSIONS

In the first part of the project, the main landing systems have been described, including the classic ones, which are ILS and MLS. Its operation, as well as its performance and requirements has been commented.

Next, the project has focused in the new approach systems. These systems use the signal from satellite systems but, as the requirements of precision and integrity for this phase of flight are the most restrictive, the satellite systems alone are not able to provide them. It is for this reason that augmentation systems are used. Augmentation systems are the SBAS, where the corrections are up linked to a geostationary satellite that will spread them into a wide area and GBAS, where the corrections are created and transmitted locally by a VHF station. Thus, the GBAS is capable of provide more accurate positioning (it is planned to provide up to CAT III) while SBAS is only able to achieve CAT I requirements.

In the second part of the project, after having described more accurately the GBAS system, the design of the front end part of the on-board corrections receiver has been made. This receiver follows the scheme of a superheterodyne receiver, with a mixer to down convert the input signal into the desired intermediate frequency.

The designed receiver, which accomplishes the minimum and maximum power input specified by ICAO, has an overall noise figure of 4.65 dB and a signal-to-noise ratio of 55 dB. The maximum power level at its output is 0.218 W (-8.9 dBW) while the minimum is $5.05 \cdot 10^{-9}$ W (-82.9 dBW).

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