CURRENT STATE OF SATELLITE NAVIGATION SYSTEMS IN THE AVIATION SECTOR

End of Bachelor Degree Thesis

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Resumen

La navegación aérea ha evolucionado desde sistemas autónomos y rudimentarios en la aeronave, pasando por sistemas de ayuda externos como el VOR, DME, ILS, MLS, TACAN, Loran C, etc. hasta llegar a nuestros días, donde se hace imprescindible la tecnología basada en sistemas globales de navegación por satélite (GNSS).

Este trabajo tiene como objetivo describir las características de todas las constelaciones actuales y todos los sistemas GNSS en funcionamiento que se están integrando en los sistemas de gestión de vuelo optimizando la navegación con rutas más precisas y trayectorias por lugares no utilizados anteriormente por falta de datos.

Palabras clave: GNSS, navegación aérea, GPS, Galileo, EGNOS

Abstract

Air navigation has evolved from autonomous and rudimentary systems in the aircraft, passing through external assistance systems such as VOR, DME, ILS, MLS, TACAN, Loran C, etc. until reaching our days, where technology based on global navigation satellite systems (GNSS) is essential.

This research assignment aims to describe the characteristics of all current constellations and all GNSS systems in operation that are being integrated into flight management systems, optimizing navigation with more precise routes and trajectories through places not previously used due to lack of data.

Keywords: GNSS, air navigation, GPS, Galileo, EGNOS

Resum

La navegació aèria ha evolucionat des de sistemes autònoms i rudimentaris en l'aeronau, passant per sistemes d'ajuda externs com el VOR, DME, ILS, MLS, TACAN, Loran C, etc. fins arribar als nostres dies, on es fa imprescindible la tecnologia basada en sistemes globals de navegació per satèl·lit (GNSS)

. Aquest treball té com a objectiu descriure les característiques de totes les constel·lacions actuals i tots els sistemes GNSS en funcionament que s'estan integrant en els sistemes de gestió de vol optimitzant la navegació amb rutes més precises i trajectòries per llocs no utilitzats anteriorment per falta de dades.

Paraules clau: GNSS, navegación aérea, GPS, Galileo, EGNOS

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Nomenclatures

AAI Airports Authority of India

$ABAS$ Aircraft-Based Augmentation System

$AGNSS$ Assisted GNSS

$ASECNA$ SBAS for Africa and Indian Ocean

$ASQF$ Application Specific Qualifications Facility

$BDSBAS$ BeiDou SBAS

$CORS$ Continuously Operating Reference Stations

CPF Central Processing Facility

$DGPS$ Differential GPS

DME Distance Measuring Equipment

$DNSS$ Defense Navigation Satellite System

$EDAS$ EGNOS Data Access Service

$EGNOS$ European Geostationary Navigation Overlay System

ESA European Space Agency

$ESSP$ EGNOS Service Provider

$EUSPA$ European Union Agency for the Space Programme

$EWAN$ EGNOS Wide Area Network

FAA Federal Aviation Administration

FIR Flight Information Region

$GAGAN$ GPS-Aided GEO Augmented Navigation

$GBAS$ Ground-Based Augmentation System

$GDPS$ Global Differential GPS

GEO Geostationary Orbit

$GLONASS$ GLobal NAvigation Satellite System

GMS Ground Monitor Station

$GNSS$ Global Navigation Satellite System

GPS Global Positioning System

GRAS Global Risk Assessment Service

GSO Geosynchronous Orbit

IATA International Air Transport Association

ICAO International Civil Aviation Organization

IGS International GNSS Service

ILS Instrument Landing System

ISRO Indian Space Research Organization

JAXA Japanese Aerospace Exploration Agency

JMA Japan Meteorological Agency

KASS Korea Augmentation Satellite System

LAAS Local Area Augmentation System

LEO Low Earth Orbit

MCC Mission Control Centres

MCS Master Control Station

MEO Medium Earth Orbit

MSAS Michibiki Satellite Augmentation System

NAS National Airspace System

NAVIC NAVigation with Indian Constellation

NDB Non-Directional Beacon

NDGPS Nationwide Differential GPS

NLES Navigation Land Earth Stations

NM Nautical Miles

OS Open Service

PACF Performance Assessment and Check-out Facility

PBN Performance Based Navigation

PHM Passive Hydrogen Maser

PSR Primary Surveillance Radar

QZSS Quasi-Zenith Satellite System

RAFS Rubidium Frequency Standard

RIMS Ranging Integrity Monitoring Stations

RTKS Real-Time Kinematic System

SBAS Satellite-Based Augmentation System

SDCM System for Differential Corrections and Monitoring

SES Single European Sky

SoL Safety of Life

SPAN Southern Positioning Augmentation Network

SSR Secondary Surveillance Radar

TACAN TACtical Air Navigation System

USSR Union of Soviet Socialist Republics

VDB VHF Data Broadcast

VOR VHF Omni Range

WAAS Wide Area Augmentation System

WRS Wide Area Reference Stations

Introduction

Throughout the previous century, human interest in flying has driven the growing development of the aerospace industry. From the beginning of the first flights that were carried out in a totally visual way to the current flights, which use sophisticated navigation methods that allow longer flights to be made in conditions inconceivable decades ago.

The current state of aviation would not be possible without the assistance of radio aids and satellite constellations used for navigation developed throughout recent history.

The evolution of technology and the investment of time and resources in research in the aeronautical sector have allowed us to reach its current state, in which aviation is accessible by the majority of the population and flights that allow us to access places thousands of miles away are performed, a concept unimaginable a few decades ago.

These advances in the sector are largely due to the inclusion of sophisticated navigation technology methods, which support aircraft to fly in conditions were visual flight is not feasible, such as during night time or in adverse meteorological conditions, among other situations which require external guidance in order to be performed with the safety conditions required.

These navigation techniques range from external radio navigation systems such as VOR, DME or ILS among others, which guide aircraft in their different flight phases, increasing safety and allowing them to be flown in unfavourable meteorological conditions and in complex geographic areas, to the use of GNSS satellite constellations, which together with augmentation systems, guide aircraft in an accurate and precise manner.

Therefore, in this Final Degree Thesis, a thorough study and analysis of the evolution of relevant technologies involved in the development of aircraft navigation will be carried out, including an exhaustive review of the current satellite constellations used for satellite navigation, in addition to an analysis of the most common radio navigation systems developed throughout the history of aviation. Some of the future projections of the navigation sector will also be discussed.

Objetives

The **main objectives** of this thesis can be summarised in the following bullet points:

- Perform a review of the historical evolution of the navigation systems used since the first aircraft flights were performed.
- Study the different radio aids developed and used nowadays.
- Describe the set of current satellite constellations used for navigation.
- Discuss the implementation of the available augmentation systems.
- Analyze the impact of the development of satellite navigation systems in the expansion of the aviation sector, discussing the effects said expansion implies in terms of the environment.

Regarding the **secondary objectives**, the following can be highlighted:

- Make a prediction on the possible future development of satellite navigation systems, based on the study of historical evolution.
- Highlight the importance of research in the air navigation sector given its relationship with the growth of the aerospace sector and with its safety.

Methodology

In order to carry out this final degree project, the usual methodology of theoretical work will be used, analyzing different studies relevant to the subject in question: current state of satellite navigation systems in the aviation sector.

An exhaustive study of the different aspects that the satellite navigation concept encompasses will be carried out, including a description of the current radionavigation systems, the different satellite constellations and the augmentation systems used, among other outstanding theoretical aspects.

Finally, some future forecasts will be proposed in the field of satellite navigation based on research, consultation and compilation of different bibliographic sources related to this type of issue.

I

Evolution of Navigation Systems

1.

Historical Background

The Wright Brothers are considered to be the pioneers of modern day aviation. By building the first heavier-than-air aircraft, they opened the door to the research that has led to the situation known to us currently. From the first planes they manufactured and flew, to the sophisticated aircraft we know nowadays, decades have past. Years of research and dedication have made it possible for the world to know the aircraft we take for granted today.

Figura 1. First heavier-than-air flight, operated by the Wright brothers in 1903, [1]

The course of this evolution and how it took place will be the first explanation covered by this thesis, linking it to the development of navigation systems, which have made this situation possible.

At first, flights were experimental and scarce, aircraft were only able to cover a few kilometers at once and at low speeds, which made it impractical to use aircraft as an alternative to more conventional types of transport such as trains. In addition, the characteristics and technical aspects of the first aeroplanes only allowed for one passenger flying at once. There were very few aircraft on the sky simultaneously.

As World War I approached, the clear advantages of using aircraft as a weapon were noticed and exploited by the governments of countries involved in it, which implied a spike in their production. Funds and time dedicated to the research and improvement of this new war tools allowed for the production of more powerful aircraft, which could cover larger distances at higher speeds and were significantly larger than pre-war machines.

Even though the production of military aircraft increased significantly due to war, this also hindered the development of commercial flights, since the technology developed during the war was specific to military aircraft, which had particular characteristics. Furthermore, civilians associated aircraft to bombarding and war, which created fear within the public. Despite this fact, the evolution in the number of flights operated with respect to the early days of aviation was noteworthy, and this was due to the technological advances made throughout World War I [16].

After World War I, the aircraft developed with the intention of using them as weapons were left purposeless for some time, until the US government decided to use the surplus aircraft for mailing. This was found to be a great decision, since it allowed for mail to be distributed more efficiently and reduced delivery times significantly. Despite this fact, the lack of navigation technology implemented in aircraft and the case that flights were operated in visual conditions, made it impossible to deliver mail nocturnally. This delayed deliveries and was found to be inefficient [16].

Figura 2. Airmail's First Day, May 15 1918 (History Net, 2021)

The impossibility to perform night flights due to visibility conditions encouraged the development of the first navigation systems. In 1921 the US army implemented the use of rotating beacons to guide aircraft following an 80 mile route between Columbus and Dayton, which allowed night flights to take place. The beacons deployed were visible to pilots following the route in Ohio in intervals of 10 seconds and this visual aid was determinant for aircraft to be operated nocturnally.

This technology was quickly implemented in flights whose purpose was to distribute mail. The US government invested more than half a million dollars in developing this guidance method in mail aircraft. This allowed for mail to be distributed across the continent in an average of 32 hours, 2 days less compared to the time taken to follow the same route via train.

An inflection point which caused a before and after situation in the aviation industry was the development in 1927 of the Ford Trimotor, commonly referred to as "Ford's Tin Goose". The fact that an already trusted figure was involved in the industry and created his own aircraft drew the public's attention to flying, moving a step further in the direction of commercial flights.

Figura 3. Ford's Tin Goose (Pinterest, 2021)

In addition to the participation of Henry Ford in the aerospace sector, another event which took place in the same year as the creation of the Ford Trimotor brought unprecedented attention of civilians to the aviation industry.

7:52 am, May 20, 1927. Charles Lindbergh, a young pilot, was about to become an American hero. After he completed the first transatlantic flight from New York to Paris without any stop, the effect on aviation was such that there was an enormous inflow of money from private investors who wanted to invest in the now well established and trusted sector.

From this moment onward, the advances made in the aviation sector continued to increase as interest in the sector encouraged the investment of research time and development. The production numbers continued to grow as research continued and by the time World War II started, the aeronautic sector was well established and aircraft were capable of flying much longer distances, as well of carrying larger amounts of payload.

Commercial aviation saw an unprecedented boost as soon as World War II came to an end. Using the considered first commercial passenger airline as an example, ex-military aircraft started being used to transport both people and cargo. These aeroplanes were retired from their use as the war ended, and then adapted to their new purpose of carrying people. In 1952, the british *de Havilland Comet* debuted as the first commercial jet airliner, however, the first proper airline did not appear until 1956, when the USSR airline Aeroflot started to operate the first sustained regular jet service, using the Tupolev Tu-104.

Then, the American aircraft manufacturers Boeing and Douglas introduced new levels of comfort, safety and passenger expectations with their models Boeing 707 and DC-8, starting in this way what is known to us today as the Jet Age. As seen in Figure 4 below, the numbers of commercial flights operated started to increase at a very fast pace at this point.

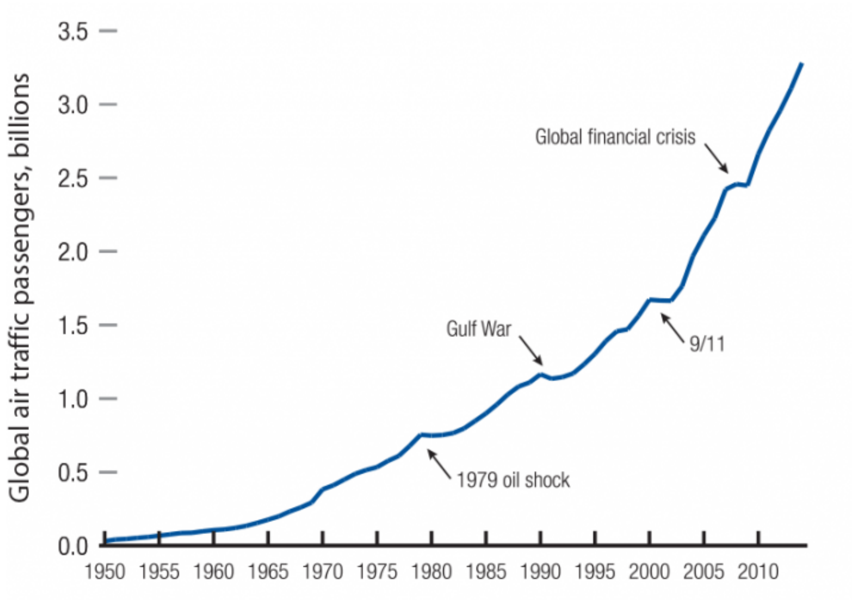

Figura 4. Evolution of global air traffic passengers (in billions) from 1950 to 2010, (IATA, 2021)

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These numbers of flights operated could not have been sustained without the pioneering efforts of Jimmy Doolittle in the late twenties to introduce instrumental navigation techniques in flights, since this vast amount of flights could not be operated safely without instrumental navigation.

1.1 Visual Navigation

Before the development of external aids used to assist the pilot of an aircraft in its guidance, pilots relied on being able to perform flights visually. In most cases, they used astro-navigation or celestial navigation, which involved using the sun, moon and stars to determine the aircraft's position [17].

At this time, air navigation was a major challenge and it was very limited in comparison to the situation familiar to us nowadays, since aircraft could only be flown in situations of good visibility, as pilots relied on their eye sight to guide aircraft safely, guaranteeing minimum separations with other obstacles, among other threats they could encounter during flights.

Therefore, situations of adversity were avoided by pilots in order to ensure the safety of flight, which limited flight possibilities. These non favourable conditions included flying at night time, conflicting meteorological conditions or flights in complex geographical locations, for instance, in highland areas, among others.

There were some rudimentary methods used at the time to establish the position of an aircraft during flights. These included astro-navigation or the use of specialised aeronautic maps.

In 1907, an International Commission for Aeronautical Charts was established in Brussels, with the objective of producing specialised and suitable air maps and charts in order to provide for basic navigational requirements.

Currently, flights are operated visually in some limited situations, however, in general aircraft rely in some kind of external aid, either for take-off and landing or during the flight. Situations which involve flying under visual conditions include ....

1.1.1 Early Air Navigators

Charles Lindbergh

1927 was a significant year for the aviation world. Charles Lindbergh set history as he became the first person to cross the Atlantic Ocean. His heroic action set a milestone for the aeronautic sector, since people became aware of the fact that long range flights were feasible and that aircraft could become a practical means of transport.

The fact that he performed this route equipped only with an Earth inductor compass, a drift sight, a speed timer (a stopwatch for the drift sight), and an eight-day clock made his action even more remarkable. Despite fatigue and slight weather deviations, he arrived at his destination within just 5 kilometers of the intended arrival site.

In addition to setting an unprecedented milestone in the aviation world in general, crossing the Atlantic also helped Lindbergh to realise that his success was in great part because of good luck. His experience made him realise long-range flights were like gambling- without external aids, the fate of the aircraft and the pilot's life were on chance's hands.

The record-breaking flight undergone by the young pilot set an example for other aviation enthusiasts to follow his steps. However, the lack of proper navigational techniques proved to be deadly in several occasions, which served as a catalyst for the development of navigation aids, since scientists realised the importance of counting with an effective and reliable guidance method, in order to avoid more unnecessary deaths and to be able to further develop the boosting sector.

As a consequence, engineers, who had previously focused on improving the technical specifications of aircraft and their performance, started working on the development of navigation techniques [18].

Figura 5. Charles Lindbergh. First pilot to perform a transatlantic flight (Famous People, 2021).

In this way, from the years 1928 to 1931, the safety and reliability of long-distance flights became a reality with the creation of a new navigation system. Accordingly, a new era of economic and specially military opportunities arose, which also arrived with considerable uncertainty.

The accomplishments made regarding aircraft navigation were in gran part achieved as a consequence of Lindbergh's historic prowess [18].

Amelia Earhart

Amelia Earhart can be considered as one of the pioneers of modern day aviation. Best known for being the first female aviator to fly across the Atlantic Ocean on her own, her ambition and will to explore the unknown contributed to awakening interest in the aeronautical sector to many people around the world, in particular, she set an example for other females, since making such accomplishments in a sector predominated by males, proved that women were capable of reaching the same achievements as their fellow male colleagues.

Despite the fact that significant advances regarding navigation techniques were achieved due to some of her predecessors, it could be discussed that Earhart's ambition drove her to aiming to accomplish milestones above the possibilities offered by the technology available at the time.

Figura 6. Amelia Earhart (Bokus, 2021)

Even though during her career as an aviator she counted with access to aircraft equipped with navigation instruments such as a ship- based radio direction finding system, in most flights she relied mainly on visual aids to fix their position, since at the time navigation aids not only were not as developed as we know them nowadays, but also pilots tended to be scarcely familiar with their use [19].

Another of the events which made Amelia Earhart famous was her unfortunate disappearance during her last attempt to become the first female aviator to perform a circumnavigation flight around the globe. It was 1937 when she boarded a Lockheed Model 10E, developed by Purdue University, where she was a visiting faculty member as an aeronautical engineering advisor. Together with her professional navigator Fred Noonan, she started what would be her last flight.

To date, this accident remains an unsolved mystery as investigators ignore the reasons behind her tragic disappearance. However, Earhart and Noonan's experience acted as a warning to other aviators not to take navigation lightly, since it is a likely theory that the lack of navigation knowledge led to their fatal outcome.

Earhart's experience is a clear example of the challenges that early air navigators faced on a daily basis. Her fate was one of the cases where the lack of access to proper navigation techniques ended fatally. This concept will be discussed in the following subsection- navigation gone wrong [20].

1.1.2 Navigation gone wrong

The fact that air navigation is a vital part of the process of a flight has been made clear throughout history. In many cases, some of the aviation pioneers who involved themselves in brave, challenging adventures to exceed the public's expectation in the related to the potential of aircraft, performed flights which ended fatally.

As previously mentioned, visual navigation implied the limitation of flights in different ways. As flying became increasingly popular, the most courageous individuals tried to break previous records by performing longer and more impressive flights. These attempts were impactful and offered fame to the record-breakers, however, they came at a high cost some times, since flying was still a dangerous activity [21].

The most clear example of an event were navigation went wrong in the awakening of aviation is the disappearance of Amelia Earhart's Lockheed Electra. The unsolved mystery of the explanation to how, what and why Earhart and her navigator never reached Howland Island, one of their last destination of their circumnavigational flight, is still a topic for discussion.

This flight was meant to be a new record- breaking achievement for the female aviator, which aimed to become the first woman to achieve the prowess of completing a circumnavigational flight of the globe.

However, Earhart's disappearance is not by far the only case of a fatal outcome to a flight due to navigation related adversities. During the period of time between the World Wars, individuals tried to achieve record- breaking accomplishments that would lead to them becoming famous. Unfortunately, many of these experimental flights led to planes crashing or aircraft disappearing never to be seen again. Navigation related issues were the cause of these fatal outcomes in many cases.

Even the aviators who managed to achieve remarkable outcomes in flights involving little to none navigational aids, agreed on the fact that these favourable results were in most cases due to luck rather than technique. They realised that, had the weather conditions for instance been slightly different, they would not have been able to complete their objectives successfully.

These accidents addressed the need of developing and implementing new navigation techniques which could be used to guide aircraft accurately and safety, reducing the possibility of a pilot getting lost mid flight or to avoid aircraft from crashing due to confusing visual conditions.

1.2 Implementation and Evolution of Radio Navigation Systems

As mentioned in the previous section, when flying became a reality in the early twentieth century, at first, simple visual aids were used during flights. However, as soon as aircraft became of military interest, these conditions were no longer sufficient. This is due to the fact that at this point, aircraft with greater ranges and capable of flying at higher altitudes were required.

First, aircraft were fitted with onboard radios, which allowed pilots to communicate with ground stations during take-off and landing mainly. This was a very useful advance since in this way pilots were able to receive instructions from the ground crew, however, the range of this radio equipment was quite limited [22].

The limitation of night flights caused by the lack of good visible conditions during night time motivated the development of a rudimentary system in 1921 formed by rotating light beacons which were visible to pilots in 10 second intervals. This advance was developed by the US military for the route between Columbus and Dayton, Ohio. This technology was soon extended to airmail, which had become popular at the time.

Still, despite the fact that this remarkable idea allowed night flights to take place with some sort of guidance, the safety standards involved were poor and this technology was not enough for long-range navigation.

After a series of fatal events which took place as aviation became more and more interesting to the public and more individuals tried to overcome the limits associated to aviation and embarking themselves on adventures that often led to them perishing while trying, as seen in some of the examples explained in section 1.1.

At this point, engineers had given little thought to the challenges associated to air navigation. From 1928 to 1931, a set of pioneering scientists developed a system of navigation which made long-distance flights feasible [23].

Between the 1930s and 1940s, aviators used a radio navigation system which involved a low frequency, four course radio range system. This system was used to indicate an aircraft's position over the Earth's surface and it worked in the following way: Morse code signals with limited ranges and patterns were emitted from specified navigation waypoints and airports. Pilots then synchronized to this frequency and guided the aircraft in such a way that they followed the direction in which the signal intensified increasingly. It worked in such a way that the signals emitted a higher volume as the aircraft approached to the broadcast point.

This idea was used to refine the technology applied to guiding an aircraft though the sky and in this way radio aids which supply the pilot with intelligence that keeps or increases the safety of flight were developed.

Prior to World War II, radio navigation could only provide a course or a bearing to a station. The invention of timekeeping technologies, such as the crystal oscillator, led to a new era of systems that could fix position accurately and were easier to use [2].

The list below summarises some of the earliest forms of navigational aids developed after World War II came to an end, highlighting some of their common advantages, disadvantages, and challenges faced [2].

- Tools: Radio Direction Finding stations, radio compasses, radio range, VOR, YE-ZB, radar, Gee, Decca, LORAN
- Advantages: Allows operation when there is no visual contact with the sky and/ or ground.
- Disadvantages: Needs complex and heavy equipment installed on the aircraft and an elaborated network of ground and space-based equipment and facilities.
- Challenges: Exposed to natural or artificial interference and more prone to technical failure.

Figura 7. Typical radio range receiver used in the late 1930s [2]

Between the end of World War II and the beginning of the jet age, which started in 1958, some aircraft used a radio-based system known as VOR flying. In this system, aircraft would receive communications from fixed ground beacons, allowing it to continue its flight path and find its position. This navigation method was proved to be quite reliable in regions which counted with satisfactory radio coverage and continued to be in use until GPS became a well established navigation method.

1.3 Introduction to Satellite Navigation

The US project started to develop a project in 1960 that would allow to improve the accuracy of aircraft position. Their idea was to improve navigation performance by using a positioning method via satellite rather than using the external radio aids that had been used since the 1940's. In this way and with this objective in mind, they developed the first satellite navigation system, the Transit.

Designed with military intentions, the Transit was the first step of the path until reaching the satellite navigation methods used in aviation today. A series of projects were developed until the first satellite from the constellation GPS, which was originally named DNSS, was launched into space in 1978.

At this point, the use of DNSS (which would later be referred to as Navstar, and then GPS) was exclusively military. However, this changed as soon as in 1983 an unfortunate accident involving a Korean Airlines aircraft took place. The aircraft was following its scheduled route from John F. Kennedy international Airport in New York to Gimpo International Airport in Seoul in September of 1983, when it accidentally entered the Soviet airspace.

Figura 8. The crash of the Korean Airlines flight catalyzed the approval of GPS use for commercial aviation (Simple Flying, 2021).

At this point, a Soviet fighter shot the commercial aircraft for crossing the border unauthorized, taking down the aircraft and killing all the passengers and crew members aboard it. This event catalyzed the approval to extend the use of the satellite navigation technology developed, since it was a wake-up call for the US government to realise accurate navigation was essential both for military and civil applications. Hence, in 1983, US President Ronald Reagan signed an executive order which allowed commercial flights to benefit from the GPS system once it was fully operational.

From this point onward, satellites were continuously developed and launched into space by the United States and the Soviet Union, which had also started a program to develop their own constellation of satellites with navigational purposes, which received the name of GLONASS.

During the first decades of the development of this new navigational technologies, it was only the United States and the Soviet Union which took part. It was not until the early 21st century that China joined them by developing their constellation BeiDou-1, followed by the creation of Galileo, Europe's own satellite constellation for navigation. Galileo was the first non-military program of this type, since the European Union created this constellation with civil intentions, unlike their predecessors. The use of GPS, GLONASS and BeiDou was originally intended to be military but different causes led to them being extended to civil purposes too.

The development of satellite constellations used for navigation will be exhaustively discussed in part II- satellite navigation. In this part, different aspects will be covered, ranging from a brief discussion of the Space Race, where the first satellites were launched into space, to a detailed explanation of the diverse satellite constellations for navigational purposes present in the different space orbits. Some of the most important augmentation systems used to enhance satellite performance will be commented as well in this part.

2.

Radio-navigation systems

In order to fully understand the following chapter of this thesis work, the concept of radio navigation and radio navigation systems must be defined before detailing any other relevant concepts.

The idea of radio navigation implies the application of radio frequencies to determine the position of an object on the Earth, either the vessel or an obstruction. Like radio-location, it is a type of radio-determination [24]. This concept can be applied to aviation in order to find the position of aircraft using radio navigation systems, which will be detailed in the following paragraph.

A radio navigation system is the set of radio navigation aids, which can be of the same or different type, that interact over radio channels or within a single unit, hence allowing to determine the position of moving objects and to solve other complex problems in navigation [24].

As previously mentioned, radio navigation can be applied to the aerospace sector with the objective of finding the position of aircraft by means of the application of radio frequencies.

It is a simple process which uses as its basic principle a set of measurements from and to beacons, in particular the following:

- Angular directions
- Distances
- Distances differences
- Velocities

Even though an exhaustive historical evolution of aviation in relation to the introduction of navigation systems was included in the first chapter of this thesis project, a brief recap will be done emphasizing on the development of the fist navigation aids.

The first navigation systems used in the aviation sector were basic and rudimentary. These were introduced prior to World War I and some of the concepts developed during this period of time have been since improved and are used in current air navigation.

In particular,

Radio navigation aids can be classified into different categories, according to their basic functioning and characteristics. These divisions include the following:

- Bearing Measurement Systems
- Beam Systems
- Transponder Systems
- Hyperbolic Systems

A summary of the main radio navigation aids used currently in the aviation sector can be observed in the table below.

To date, the aviation sector still heavily relies on radio-navigation aids, given the lack of full availability of satellite constellations, since most have a military nature and part of their services are encrypted to the public user.

VOR

The VOR, which stands for Very High Frequency Omnidirectional Range, was developed in the United States by the Washington Institute of Technology in the 1940s decade. Even though it is currently the most deployed system around the world in terms of air navigation, the objective is to substitute it eventually by PBN navigation: RNAV-RNP.

The system of a VOR is formed by a ground installation, which includes an emitter and an antenna, and an installation on board of the aircraft, which is formed by an antenna, a receptor, an indicator and a servo-amplifier.

Figura 9. Ground Station of a VOR [3]

The functioning of the ground installation is based on the phase difference between the two signals it emits, which include one of reference and a variable one.

Regarding the reference signal, it is an omnidirectional sigal with a frequency of 30 Hz, transmitted from the station in a circular way, which keeps it constant in all directions.

The variable signal, which also has a frequency of 30 Hz, is transmitted by means of a directional antenna which turns at a speed of 1800 revolutions per minute.

The VOR emits an infinite number of beams known as radials which are identified by their magnetic marking as they leave the station. Despite the fact that the radials are infinite, the on-board equipment of the aircraft is only capable of identifying 360 of them. The magnetic north is the reference point used to measure the phase difference between the two signals, and at this point, the signals are exactly in phase. At any other point around the station, the phase difference between both signals varies according to their distance from the magnetic north.

It is important to bear in mind that all VORs have a çonfusion cone". This concept implies that when a signal is emitted from a VOR ground station, certain blind zones where the signal is non existent. These areas are denominated çonfusion cones", and they are located above the station. When an aircraft is flying directly above the station, through the confusion cone, it does not receive any signal. Since it has a shape of an inverted cone, the amplitude of this area increases with altitude.

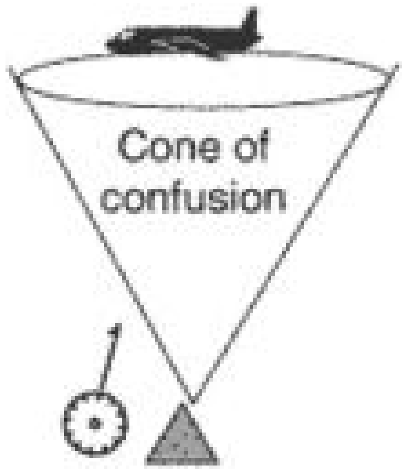

Figura 10. Confusion Cone of a VOR navigation aid, [4]

The identification signal consists on a tone with a frequency of 1020 Hz, whose amplitude is modulated to that of the carrier by means of a radio frequency signal, which emits and indicative of the station in Morse code. The identification consists on two or three letters transmitted at a speed of 7 words per minute, being emitted once every 30 seconds. For instance, an example of the identification of two VOR stations could be the following:

- Valencia VOR station: VLC 116.10 MHz
- Calles VOR station: CLS 117.55 MHz

Regarding the range of the VOR, it depends on the type of emitting device used by the ground station, as well as other factors, such as the orography of the terrain. Despite the fact that it depends on the previously mentioned factors, it is usually stated that the range varies from 25 NM to 156 NM. Usually, a range of 25 Nautical Miles is provided by T-VOR terminals, which tend to be used just in approach procedures at an altitude below 12000 ft. In the case of larger ranges of 156 NM, these are provided by H-VOR or VORs of great altitude, which provide a service for aircraft flying at an altitude above 75000 ft.

About the equipment used on-board of the aircraft, it must be a receiving equipment capable of decoding the information received from the ground emitter, and capable of providing the position of the receptor in relation to the emitter. The main aim of the VOR technology is to allow the pilot to select, identify and keep the wanted radial with relation to a VOR transmitting ground station.

The components of the on-board equipment are the following:

- Antenna
- Receptor
- Servo-amplifier
- VOR indicator

The purpose of the receptor is to measure the phase difference between the reference signal and the variable one, both emitted by the ground equipment. It counts with a frequency selector which is used to search for the desired beacon.

In the case of the servo-amplifier, the receptor receives the electromagnetic energy and it converts it to electric impulses, which must be amplified in order to produce the required deflections for the VOR indicator.

The purpose of the VOR indicator is to show the aircraft's pilot its location with respect to the ground station at any time, with enough clarity and precision in order for the pilot to be able to keep the aircraft in the determined route.

Regarding the precision of the equipment, the theoretical precision, which is only accomplished in the most favourable scenarios, is of 1.5º. About the practical precision, which is the one typically obtained, it oscillates between 2.5º and 5º. This precision arises as a result of the compound quadratic error precedent of the ground equipment, on board and pilotage errors, which all contribute to reducing the precision of the equipment used.

DME

Another radio navigation aid which is very used nowadays in terms of air navigation is the Distance Measurement Equipment (DME). It consists on a distance measuring system which works as a secondary radar. Its functioning is based on measuring the time interval between the interrogation, which is initiated by the aircraft, and the response generated by the ground equipment.

This system works in the UHF band, which implies that it is not conditioned or influenced by the atmospheric errors. As an inconvenience associated to this band, it can be stated that the range of the signal is limited to 200 NM for aircraft flying at high altitudes, which limits the usage of this navigation tool to medium and short distances.

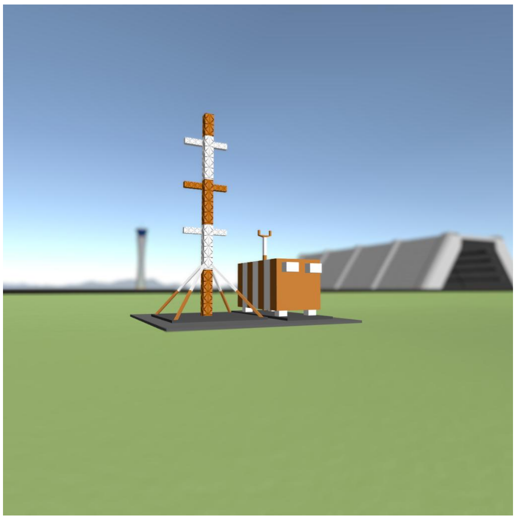

Figura 11. DME Ground Station, [5]

The error associated to the measurement of distances using this system is estimated to oscillate around $\pm$ 100 m, or 0.4 % of the distance, in the case of larger distances. The variation DME/P is another option available. It consists on an improved conventional DME which allows to obtain an improved precision in the approach phase.

With the objective of being able of locating the aircraft in polar coordinates, it is common to install in the same spot both a VOR station and a DME, or in other cases a TACAN (VOR-TAC stations), in order to satisfy in this way both the civil and military requirements.

ILS

The ILS is a navigation tool used during the approach and landing phases of an aircraft's flight. The final part of a flight starts in the approach phase, which encompasses the part of a flight where the aircraft makes the transition from normal flight conditions (cruise flight) to the beginning of the landing.

The aim of an approach is to take the aircraft to the contact point with the runway, in the normal conditions required for a landing procedure. Landing begins in the moment when the landing gear of the aircraft touches the runway and it ends when the aircraft reduces its velocity enough to be able to exit the runway or stop there.

More specifically, the ILS is used in APV-Precision Approaches (LPV), where both horizontal and vertical guidance are provided.

The ILS device is formed by three different sub systems which transmit energy into the space, providing directional radiation diagrams which allow to fix the position of the aircraft in azimuth, elevation and to provide distance milestones at 300m, 1000m and 7000m.

The three previously mentioned sub-systems of an ILS are the following:

- LOC-LLZ
- Glide Slope, GP
- Radio-beacons

Figura 12. ILS Station on an airport, [6]

The sub-system LOC-LLZ allows to locate the aircraft on the vertical plane, which contains the axis of the runway. The LOC-LLZ works with a band of 108-112 MHz, which it shares with the VOR, and its amplitude is modulated by two signals of 90 and 150 Hz.

It is formed by a set of dipoles of 12 and 24, which transmit electromagnetic energy and generate a radiation diagram in such a way that the depth of the signal's modulation is a function of the receptor's position with respect to the vertical plane which contains the axis of the runway.

The localizer is installed in the runway's axis, at an approximate distance of 300 m, in such a way that the centre of the antenna matches with the runway's axis. The nominal coverage offered by the localizer is of 25 miles for a sector enclosed between $\pm 10^{o}$.

Regarding the glide slope, its purpose is to indicate the gliding path (3^{o}) that the aircraft must follow until reaching the runway's threshold. This is done by means of an antenna installed in such a way that it is displaced from the runway's axis by between 120 and 180m, at a distance from the runway's threshold which depends on the angle of the descent path. The frequency oscillates between 328.6 MHz and 335.4 MHz.

Its antenna is built by two dipoles which count with a reflector which is in charge of limiting the backward radiation and are installed in a vertical pole. The signal received from the aircraft's receptor is the vector sum of the signals radiated straight from the antennas and by the signals reflected from the ground. Hence, the reflecting terrain must be as flat as possible.

The radio beacons or markers used provide information about the distance to the threshold of the landing runway, at given points of the path, rather than in a continuous way.

The types of radio-beacons used are the following:

- Outer Marker Beacon (OM): The most distant beacon, located at approximately 7 km from the contact point and modulated by a 400 Hz signal.
- Middle Marker Beacon (MM): Located at 1 km from the contact point and modulated by a 1300 Hz signal.
- Inner Marker Beacon (IM): Located at 300 metres from the contact point and modulated by a 3000 Hz signal.

NDB

This radio aid is a radio beacon that works by transmitting a permanent signal in all directions. In order to identify itself, the transmitter uses a slow Morse code signal formed by two or three letters. Usually, the letters used have some connection with the name of the lighthouse or station.

These beacons are capable of transmitting signals in the range of 190 to 1750 kHz, however, most NDB beacons transmit signals with frequencies within a range of 250-450 kHz. The range offered by a NDB system oscillates between 10 and several hundred nautical miles [25].

These radio aids tend to be situated near airports, since they are used to provide service to approaching and departing aircraft.

Previously, these tools were also used to provide support during the en route phase of a flight, however this technology has become obsolete in this ambit since the development and implementation of the GNSS satellite constellations as navigation tools [26].

NDB is the oldest type of radio navigation aids and it is currently beginning to become obsolete in spite of the newest forms of navigation tools developed, however, it is still functional at the moment [25].

This navigation technique must be complemented with an on-board device known as ADF, which stands for Automatic Direction Finder. Sometimes, this tool is also referred to as Radio Magnetic Indicator (RMI) [25].

Figura 13. NDB station, [7]

TACAN

Another radio aid used, in particular by the military, is Tactical Air Navigation, TACAN. It is a polar-coordinate system used for air navigation that provides distance information which can be used for the guidance of aircraft. To do so, they combine information precedent from distance measuring equipment (DME) and bearing information.

A polar coordinate radio navigation system is a geometric system which can be used to situate points on an aircraft. It tends to be used in order to plot antenna directional patterns.

The information provided by this radio aid tends to be displayed by two different meters, one indicates the distance from the aircraft to the beacon in the ground, in nautical miles, and the other one provides the direction of flight, given in degrees-of-bearing, to the ground beacon [27].

Using TACAN equipment, a pilot is capable of receiving a bearing to a location and the distance to a particular location. This information can be used for the following purposes:

- Flying directly to the location of the beacon.
- Using the information provided about the bearing and distance of a particular beacon to fix the aircraft's geographic position.

It works in a frequency band between 960 and 1215 MHz, overlapping the DME frequency range. It combines a VOR-DME and includes an azimuth feature that provides more accurate navigation [28].

Figura 14. Early TACAN ground system, [8]

LORAN

The LORAN, or LOng RAnge Navigation, is a navigation system developed by the United States during World War II in order to provide a guidance method for military aircraft. Its use was intended for long range flights, since its accuracy was low in comparison to other contemporary navigation methods such as the British GEE system, which were used for short range flights.

Even though it was decommissioned in 2010, as it was substituted by newer, more accurate navigation methods, this medium range hyperbolic radio navigation system, proved to be incredibly useful, specially to the US Coast Guard, where it was used for the first time. To date, some components of the LORAN system are used as a backup to the GPS constellation.

The LORAN system enabled a receiver to find its position by means of the utilisation of multilateration principles, used to compare the reception times of low frequency radio signals transmitted by ground radio beacons and to compute the differences in these times. These beacons could be found in chains or groups, formed by one master transmitter and between 2 and 5 secondary transmitters, also known as slave transmitters.

In order to increase the accuracy of this navigation tool, the multilateration principles involved in the LORAN technology were combined with technologies capable of measuring the phase shift of such signals, improving in this way the fix accuracy. This improvement was developed during the post-ware years and was denominated LORAN-C, whereas the original navigation aid was designated LORAN-A.

LORAN-A systems were substituted by the newly developed LORAN-C, however, some LORAN-A chains remained in use until 1980. The fact that LORAN-C was able to provide both long-range and very accurate signals by combining multilateration and phase shift technologies made it very popular in terms of air navigation.

Regarding the architecture of LORAN-C, its transmitters were distributed into chains of between three and six stations, a Master and a flexible number of secondary stations. The difference between master and slave stations in terms of identification was that master stations radiated pulses in bursts of nine, whereas slave stations emitted bursts of eight pulses.

MLS

Another radio aid intended mainly for aircraft approaches is the Microwave Landing System (MLS). It is an precise radio guidance system which can be used in diverse weather conditions, whose use was intended for large airports, and its purpose is to assist aircraft during their approach phase to airports [29].

This system allows aircraft to determine the moment in which they are aligned with the runway during an approach, enabling the performance of a safe landing. MLS was developed with the intention of substituting the ILS aids installed in airports, since it was found to provide a series of advantages with respect to the ILS navigation aids [29].

These advantages included the fact that when using MLS, a more varied selection of channels is available, which implies the fact that interference with nearby installations can be avoided. Furthermore, MLS guarantees outstanding performance in adverse weather conditions, and approached from wider areas around the airport are enabled due to the wide vertical and horizontal capture angles associated with MLS navigation.

Despite the fact that the intention was to completely substitute ILS landing approaches by MLS ones, this widespread deployment of MLS did not become a reality. This was mainly due to the cost associated with the installation of this type of system, which proved to be too costly for the advantages it provided. This means that, even though MLS was superior to ILS technology, its advantages did not justify the economic difference. In addition, the simultaneous development of GPS limited the success of MLS, since GPS could also be used during the approach phase, providing a similar quality service, at a much lower cost, since no additional equipment is required in airports.

Regarding its functioning principle, MLS uses transmitters which use 5 GHZ signals at the landing place. This signals employ passive electronically scanned arrays to send scanning beams towards an aircraft in the approach phase. A receiver installed in the aircraft then calculates its position by measuring the arrival times of the different beams once it enters the scanned volume.

RDF

The Radio Direction Finder was the first radio navigation system developed, some of the early air navigators, such as Amelia Earhart, used this system to guide their aircraft through long-range flights, aiding them in their record-breaking adventures.

In order to find the direction to a broadcasting antenna, an aircraft's pilot had to tune in a radio station and use a directional antenna. Then, another measurement recorded using another another station was obtained, and using the method of triangulation, both directions were plotted on a map where the intersection between both directions could be seen. This intersection represented the aircraft's location.

The first RDF systems usually employed a loop antenna, which consisted on a reduced loop of metallic wire mounted in such a way that it could be rotated around a vertical axis. These loop antennas are common in most aircraft and ships manufactured prior to the 50s decade.

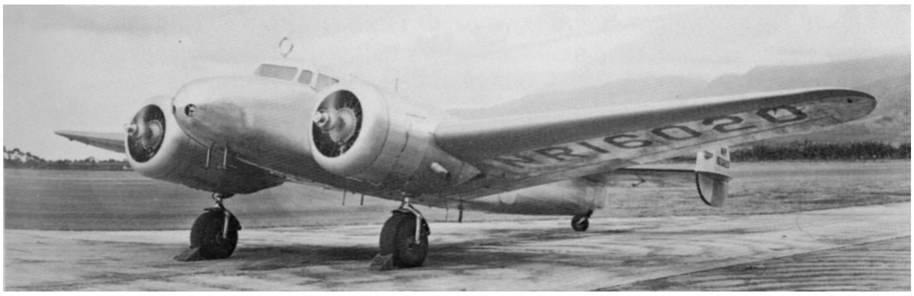

Figura 15. Amelia Earhart's Lockheed Model 10 Electra with the circular RDF aerial visible above the cockpit, [9]

The size of the receiving antenna used in RDF systems depends on the wavelength of the signals involved, being both variables directly proportional. Hence, since the frequencies of signals used in aviation communications tend to be very high, the size of the receiving antennas are usually of a reduced size [9].

From the first RDF systems developed to the ones used currently, many variations have been used, according to the evolution of technology over the decades. To date, modern direction finder systems are formed by a set of antennas of a reduced size, fixed to a circular card, which contains all the processing.

II

Satellite Navigation

1.

The Space Race

Satellite navigation would not be possible without the period of history in the mid twentieth century, between the sixties and the seventies decade, commonly referred to as the Space Race.

After World War II came to an end, tension between the United States of America and the Soviet Union began to build up. A series of events led to both of the world's great powers competing to hold the title as the leader in terms of space missions accomplished.

The launch of the Sputnik-I by the soviets was an inflection point for the evolution of history. An image of this first human made body launched to space can be seen in Figure 16. As it can be observed, it consisted of a small spherical object without any particular purpose other than taking the lead in the race that had just began between both powers.

Surprised by the soviet's first step in the winning direction, the American engineers worked around the clock in order to develop the Explorer-I, United States' first artificial satellite launched into space. Again, the sole purpose of this satellite was to level up to the Soviets, who had taken the lead in the race.

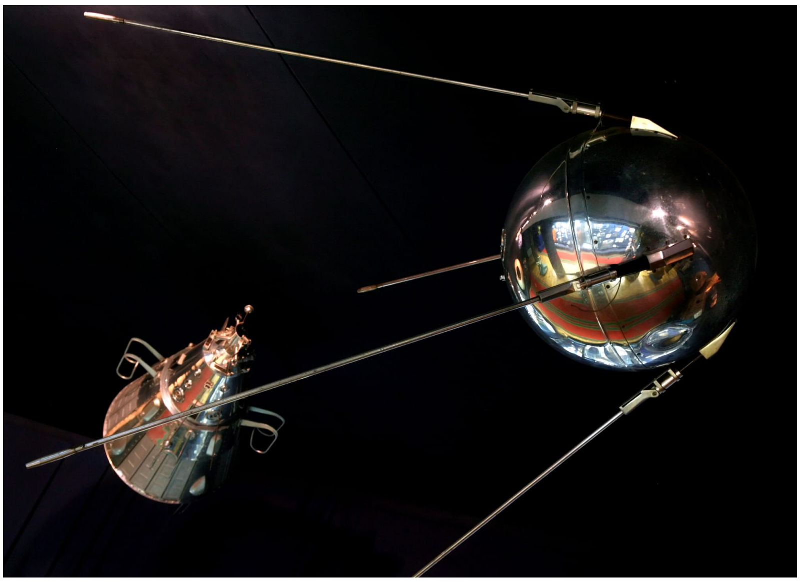

Figura 16. The first satellite launched to space, the soviet Sputnik (History, 2021)

The series of events that followed the respective launches of the first Soviet and American satellites were continuous trials from both countries to overtake the other in the space race.

Despite the fact that, as previously mentioned, the first artificial bodies launched into space did not have specific technical purposes, the research involved in learning how to put objects into orbit would be applied later with satellites which did have a mission.

These concepts, studied for years, allowed for the development of more sophisticated satellites, such as the Intelsat-I. Launched in 1965 by the United States, this satellite, commonly referred to as *Early Bird*, was used for civil communications. It was the first satellite to reach the geostationary orbit, 36000km above the Earth's surface, which did not have military applications.

In Table 1 included below, a summary of the main relevant dates regarding the space race between the United States of America and the Soviet Union can be observed.

Date	Event
1957	The first artificial satellite (Sputnik-I) is launched to space by the USSR. The space race begins.
1958	The US launched their first satellite (Explorer-I).
1961	Soviet cosmonaut Yuri Gagarin becomes the first human to orbit the Earth.
1965	First civil GEO satellite (Intelsat-I).
1969	Neil Armstrong becomes the first man to walk on the moon's surface.
120	Más allá de la región de absorción meteórica.
200 - 250	Resistencia del aire próxima a cero.

Tabla 1: Significant dates of the space race between the United States and the Soviet Union [15]

Research was invested in the sector and after satellites with diverse purposes were put into orbit successfully, the US military launched the Transit satellite in the 1960s. This was the first satellite whose mission was to implement satellite navigation. Developed with military intentions, the Transit set a step in the direction of implementing satellite navigation to guide aircraft.

This was a great technological improvement with respect to the previously used radio navigation aids, and the advantages of using satellite navigation as an aircraft's guidance were soon noticed.

2.

Satellite Constellations used for Navigation

Satellites have been present in space since the Sputnik-I was launched into orbit by the Soviet Union in 1957. Ever since, the will to discover and explore the unknown intrinsic to the natural behaviour of humans, has led to launching thousands of different artificial satellites into space.

These satellites vary greatly in size, weight, materials or altitude at which they orbit the Earth, among other technical aspects, and their purposes range from observation to communications, including many other important functions, either civil or military intended.

To date, the use of GNSS satellite constellations is wide spread and incorporated into our lives in a range of diverse applications. The interest of this thesis will be focused on the use of satellite constellations for navigation purposes, however, it is worthy to mention that air navigation occupies a reduced portion in the wide range of uses offered by this technology.

In terms of aviation, the main applications can be divided into regulated professional and non-regulated, recreational use, and the following uses of GNSS technology can be highlighted [30]:

- Navigation, specially PBN
- Emergency transmitters
- Surveillance and monitoring
- En route navigation
- Alarm systems
- Beacons for search and rescue operations

In this section of the thesis, the different satellite constellations available for navigational use will be discussed, sub classifying them into constellations that offer either global or regional coverage.

A table that summarizes the satellite constellations used for aircraft navigation currently occupying space can be seen below in Table 2.

Name	Country	Launch Date	Coverage
GPS	US	1978	Global
GLONASS	Russia	1982	Global
BeiDou	China	2000	Global
GALILEO	Europe	2011	Global
QZSS	Japan	2010	Regional
NavIC	India	2018	Regional

Tabla 2: Satellite Constellations used for Navigation.

Table 2 shows some of the basic, most relevant characteristics of the satellite constellations, however, each of them will be analysed in the following sub section, describing in detail their functioning, launch dates and orbit of their satellites among other important features of these satellite constellations used for navigation.

2.1 Global Constellations

Global constellations of satellites are those that can offer a coverage of ...

Currently, four fully operational global satellite constellations are present in space. These are the American GPS, the Russian, previously soviet, GlONASS, the Chinese BeiDou and the European GALILEO. The four of them will be exhaustively analysed in the following subsections.

Despite the fact that each of the global satellite constellations have particular features that make them stand out from the others, since their purposes are the similar- to provide a global coverage of the Earth to provide satellite navigation, they share some common characteristics.

These common attributes have been listed below:

- Despite slight variations among altitude at which their satellites orbit, all satellites of the different constellations are placed at the MEO at approximately 20000 km above the Earth's surface.

- They share similar periods of approximately 12 hours, which means that they all perform nearly two revolutions of the Earth each day.

- All constellations are composed by an approximately equal number of satellites, ranging between 24 and 30

- Similar precision for public use ranging between 0.3 to 5 metres

- They all offer a global coverage of the Earth's surface

Their most noteworthy differences exist mainly on more specific, technical aspects of their functioning. These will be discussed in detail for each satellite constellation.

As a general trend, the number of satellites in orbit with navigational purposes have been increasing since the launch of the first satellite belonging to a constellation with navigational purposes. Figure 17 illustrates this evolution along the previous decades, specifying the numbers of each of the global constellations of satellites used for navigation- GPS, GLONASS, BeiDou and Galileo.

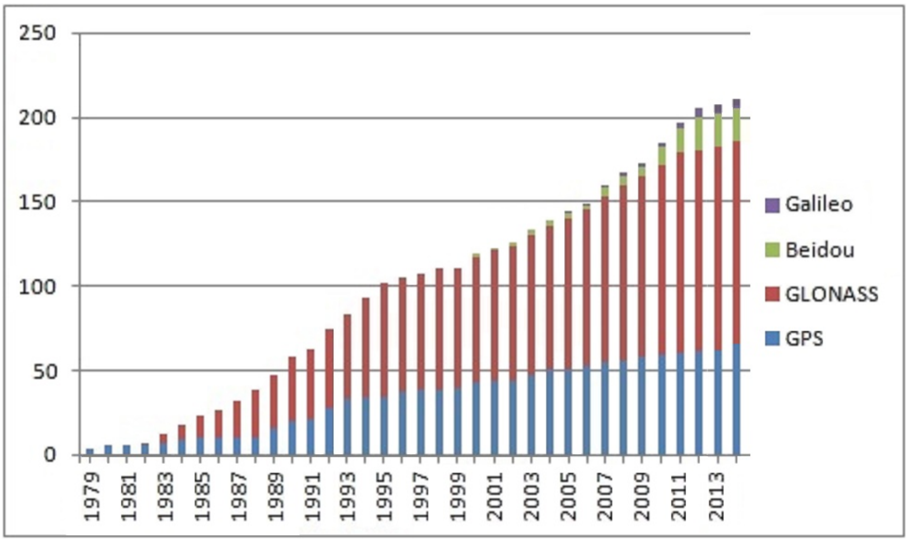

Figura 17. Evolution of the number of satellites in global constellations from 1979 to 2013 (Wikipedia, 2021).

In the previous Figure, it can be observed how in. general terms, the number of satellites have increased since the beginning of the era of satellite constellations with navigational purposes. In particular, this graph provides information for the constellations GPS and GLONASS mainly, since by the year 2013, the program Galileo had just started and BeiDou had few satellites in orbit at this point, given that it was still a constellation which provided regional coverage.

GPS

The Global Positioning System, most commonly referred to as GPS, was the first satellite constellation to be launched into space. Designed for military purposes, a series of unfortunate events led to the approval of extension of its use in passenger or commercial aviation.

The project was authorised in the early seventies for military use, in particular in 1973, with the objective of overcoming the limitations from previously used navigation systems. The development of the project was in great part based on the technological advances made when the first satellite navigation system was successfully tested in 1960. Transit consisted on a set of five satellites which were capable of providing a navigational fix approximately one time each hour.

Despite the fact that the project started in 1973, it was not until the year 1978 that the first satellite of the GPS constellation was launched into space. The navigation system became fully operational and globally available in 1995.

Currently, the Global Positioning System is the most used GNSS satellite constellation in terms of navigation.

Once the the historical development of this American GNSS system has been reviewed, the most technical aspects of the satellite constellation will be discussed. As the other global constellations, the satellites of the GPS system are placed in the Medium Earth Orbit, which implies that they are located at an altitude of 20180 km above the Earth's surface.

Even though the original project was designed to create a constellation formed by 24 MEO satellites, there are currently 32 satellites in orbit, 31 of them being operational. These satellites are arranged into different blocks, IIA, IIR, IIR-M and IIF.

The specifications of each of the previously mentioned blocks have been summarised in Table 3.

Block	Satellites	Operating Satellites	Launch Dates	Clock
IIR	12	11	1997-2004	Rb
IIR-M	7	7	2005-2009	Rb
IIF	12	12	2010-2016	Rb, Cs
IIIA	4	4	2018-	Rb

Tabla 3: Operational blocks of satellites within the GPS constellation

Regarding block IIIA, satellites are still being launched into orbit, with an expected total of 10 satellites planned to take part in this block. Block IIR experienced one launch failure.

In addition to the currently operational blocks of satellites, the GPS constellation originally had the blocks I,II and IIA. These blocks no longer have any functioning satellites, however, due to their historic significance, their information has been summarised in Table 4

Block	Satellites	Operating Satellites	Launch Dates
I	8	0	1978-1985
II	9	0	1989-1990
IIA	19	0	1990-1997

Tabla 4: Non-Operational blocks of satellites within the GPS constellation

Concerning the first block, I, it originally planned to launch nine satellites in total, however, only eight of the total launches were successful. The block IIA still plays a role in the GPS constellation, since it holds eight reserve satellites.

The precision provided by the current satellite constellation ranges between 0.3 to 5 metres. This system operates using the frequency bands L1,L2 and L5 signals mainly.

The US government plans to create new satellite blocks in the following years, with the objective of retiring some of the eldest satellites, renewing the satellite constellation in this way.

GLONASS

As soon as the US started to create the GPS satellite constellation, the formerly soviet, now Russia responded as expected by announcing the creation of their own version of the GPS system - GLONASS.

The distribution of 24 total satellites in this constellation is made in three orbital planes, with each of the planes containing eight equally spaced satellites. In order to provide global coverage, the 24 satellites are needed, however, only 18 satellites are required to provide coverage to the area enclosed by the Russian territory.

The satellites in the GLONASS constellation are arranged into several series, in a similar way to the distribution of the GPS constellation. This arrangement can be seen in Table 5.

Series	Launch	Status
GLONASS	1982-2005	0ut of service
GLONASS-M	2003-	In service
GLONASS-K1	2011-	In service
GLONASS-K2	2022-	Test Satellite
GLONASS-V	2023-2025	Design Phase
GLONASS-KM	2030-	Research Phase

Tabla 5: Series of satellites within the GLONASS constellation

In Table 5 all the series of the GLONASS constellation have been summarized, including the original GLONASS series, which is out of service, and some of the series which are still being tested or are in diverse status, such as in the design or research phases.

The main differences within the different GLONASS series lie within the technical improvements made due to years of research from the first launch of one series to the first launch of the next. A significant improvement made since the first generation to the third one, series K1, is the increase in the lifespan of satellites, which currently is of 10 years. Another improvement is the weight of the satellites launched, which was significantly reduced in nearly 50 % from the M generation to the K1 series. This weight reduction was made possible due to the fact that the first unpressurized satellites were launched at this point.

An advantage of the Russian constellation with respect to GPS is the fact that it's orbit makes this system particularly suitable for very high latitudes, either north or south, which makes it's use preferential for areas of geographic high latitude were the service offered by GPS is of a lower quality.

The orbits of the satellites in the GLONASS constellation are designed to have an inclination of 64.8º, a period of 11 hours and 15 minutes and an altitude of 19100 km, belonging to the MEO orbit. Regarding the frequencies of the signals involved, mainly the bands G1,G2 and G3 are used. These provide frequencies within the ranges of 1.593–1.610 GHz in the case of G1, 1.237–1.254 GHz in the case of G2 and 1.189– 1.214 GHz for the G3 band.

BeiDou

Despite the fact that the Chinese constellation started offering regional coverage over China under the name BeiDou Satellite Navigation Experimental System or BeiDou-1, it eventually evolved into a global satellite constellation, similar to GPS, GLONASS or Galileo. The group BeiDou-2, also referred to as COMPASS, eventually substituted the original BeiDou-1.

In fact, during the initial development of the BeiDou project, a three step plan was proposed:

1. By 2000: Construction of BDS-1 completed to provide services to China
2. By 2012: Construction of BDS-2 completed to provide services to the Asia-Pacific region.
3. By 2020: Construction of BDS-3 completed yo provide global services.

The BeiDou Navigation Satellite System (BDS) was originally developed as a consequence of the risk of being denied access to the American system GPS, however, the idea emerged in the 1980s. Initially, three satellites were launched to offer a regional coverage of China and surrounding areas, forming BeiDou-1. The first satellite of the original constellation, BeiDou-1A, was launched on October of 2000.

BeiDou-1 was finally dismissed in 2012, being substituted by BeiDou-2, which became operational in 2011. Since then, it has been offering its service to customers in the Asia-Pacific region.

The orbits used by the satellites present in the BeiDou constellation include the Medium Earth Orbit (MEO), the Geostationary Orbit (GEO) and the IGSO orbit.

Figura 18. Logo of BeiDou constellation, (BeiDou Navigation Satellite System, 2021).

The main architecture of the BeiDou constellation consists on three different segments:

- Space Segment

- Ground Segment
- User Segment

The space segment, which was previously described by detailing the number and nature of the different satellites present in the constellation, consists of a number of satellites located in different orbits- GEO, MEO and IGSO.

Regarding the ground segment, it consists of different ground stations, which include master control stations, time synchronization or uplink stations and monitoring stations, in addition to facilities used to operate and manage the inter-satellite link.

Finally, the user segment is formed by diverse types of BeiDou basic products, systems and services.

A summary of the satellites present on each system has been included in the table below.

Block	Launch Period	Satellites Launched	Active Satellites
1	2000-2006	4	0
2	2007-2019	20	12
3	2015-present	35	30

Tabla 6: Summary of satellites in the BeiDou Constellation.

From Table 6 the structure of the BeiDou Navigation System can be observed. It can be appreciated how Block 1 (BeiDou-1) is currently inactive, since it has no operative satellites and Blocks 2 and 3 are active simultaneously. The constellation has a total of 42 operating and healthy satellites at the moment, distributed between Blocks 2 and 3.

GALILEO

The last global constellation to become fully operational was the European Galileo, developed by the European Union and the European Space Agency (ESA), it became fully operational in 2016, despite being planned to become operational earlier. It is the European alternative to the American GNSS system GPS, and it is the first GNSS system developed with non-military intentions.

Once the program is completed, the constellation will be formed by satellites evenly spread throughout three orbital planes, which will be inclined at an angle of 56º to the equator. The period of each satellite will be of approximately 14 hours, implying nearly two revolutions will be performed around the Earth per day. As a redundancy measure to ensure functioning in case of failure, an additional satellite will be placed in each plane.

It is intended for Galileo to be composed by 24 fully operational satellites and 6 in-orbit spares, all at 23000 km above the Earth's surface, at the MEO orbit.

Despite the fact that Galileo is an autonomous GNSS system, it is completely inter-operable with other existing GNSS navigation systems such as the American GPS or the Russian GLONASS. Inter-operability between satellite systems guarantees an increase in coverage, accuracy and reliability of the measurements obtained by the different satellite constellations [31].

Regarding the clocks present in the satellites conforming the constellation, the usable satellites mainly use PHM clocks (Passive Hydrogen Maser), with an exception of one operative satellite which uses a RAFS clock (Rubidium Atomic Frequency Standard).

All the satellites which form the Galileo constellation were launched from the Guiana Space Centre in Kourou, French Guiana, given the appropriate latitude from this site. The most recently launched satellites used the Ariane 5 as a rocket carrier, but the earliest Galileo satellites to arrive into orbit used the Soyuz capsule to arrive to their destination.

Figura 19. The Guiana Space Centre in Kourou, French Guiana (Pinterest, 2021).

2.2 Regional Constellations

Regional constellations of satellites are those that can offer a coverage of a particular country or region, opposite to the four constellations described previously, which offer a global service.

Some constellations, BeiDou in particular, started being regional constellations which expanded until becoming a global service. However, there are other which currently work regionally, with plans of expanding in the near future.

At the moment, there are two regional constellations of satellites, the Indian NAVIC, also referred to as IRNSS, and the Japanese constellation QZSS. Both constellations will be discussed in detail in the following subsections.

Constellation	Period	Altitude	Precision	Coding
QZSS	23.93 h	32600 km, 39000 km	1m (public)	CDMA
NavIC	23.93 h	36000 km	1m (public)	CDMA

Tabla 7: Comparison between QZSS and NavIC constellations.

In the same way that global constellations shared some common properties, so do regional constellations. A brief summary of these common properties are discussed in Table **??**, before highlighting some of the most remarkable aspects of these separate navigation systems.

NAVIC

Also referred to as IRSS, NavIC is a regional constellation of satellites used for navigation purposes. It was approved in May of 2006 and developed by the ISRO to offer navigation service to India, as an alternative to the GPS.

Currently formed by a total of seven satellites, it offers full coverage to the whole Indian region and all areas extending up to 1500km around the country. These satellites are distributed as follows- three satellites are located in the GEO orbit and the remaining four in the GSO orbit.

As previously mentioned, the space segment would consist of a total of seven satellites. Another part of the architecture of this satellite constellation includes the ground segment, which is formed by a Master Control Centre (MCC), ground stations involved in tracking and estimating the satellite's orbits, in addition to ensuring the integrity of the network, and additional ground stations (TTC).

These additional stations are in charge of monitoring the satellites and issuing radio commands to them when required. Regarding the MCC, its purpose is to estimate and predict the positions of all the satellites in the constellation. Furthermore, the MCC calculates the integrity, makes corrections in the clock and of ionospheric nature, in addition to running the navigation software.

NavIC or IRNSS provides two different types of services, which are the Standard Positioning Service (SPS) and the Restricted Service (RS). Unlike the service RS, which is only available for authorised individuals, the SPS is a service which can be accessed by all users [32].

Other purposes for which the IRSS or NavIC system was developed, which are not related to air navigation, include improving the precision of time keeping, disaster management or mapping among many others [33].

Figura 20. Logo of NavIC (GPS.gov, 2021).

QZSS

Finally, the second regional system and last constellation to be discussed in this section is the QZSS constellation. Also known as Michibiki, this GNSS constellation consists on a system formed by one geostationary and three geosynchronous satellites which offer full coverage over Japan and the Asia-Oceania region. It acts as an enhancement for the GPS constellation and it is a regional time transfer system.

Developed by the Japanese government, its first satellite was launched in 2010, however, its services did not become available until 2018. At the moment, there are only four satellites in orbit, however, there are plans to extend this constellation and make it an independent satellite navigation system by 2023, with a total of seven satellites [34].

The idea of implementing this constellation, which works as an augmentation system, arose in order to obtain very precise and reliable positioning services around the Asia-Oceania area, with a focus in Japan, which are compatible with the American GNSS system, GPS.

This was due to the fact that, even though GPS offers coverage for almost every part of the planet, there were some areas of the Japanese geography which received a weak or even non-existent signal from the United State's constellation. Hence, the need to develop an enhancement for the signal in order for this country to rely on accurate and precise measurements came to the attention of the country [10].

The satellite's orbits are designed in such a way that there is always at least one satellite directly over Japan, with an elevation of at least 60º. The geosynchronous orbits form an analemma, with a separation of approximately 120º between each satellite. The pattern followed can be appreciated in Figure 21.

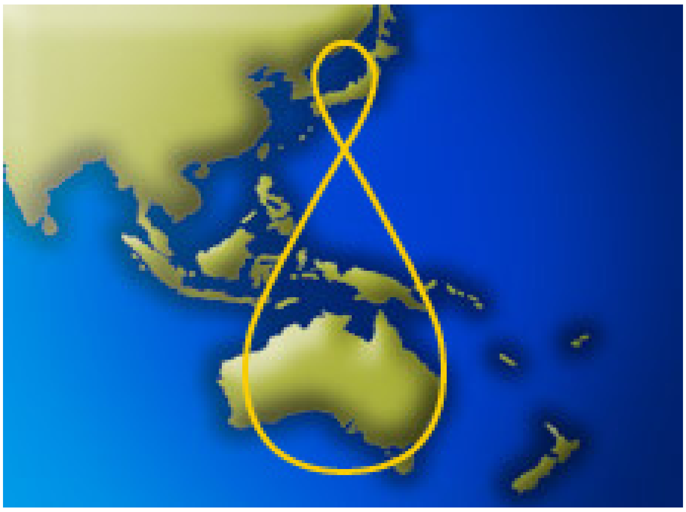

Figura 21. Analemma pattern followed by the three geosynchronous satellites of the QZSS constellation [10]

3.

Augmentation Systems

A GNSS augmentation system is defined as a system that improves the functioning of GNSS by increasing its accuracy, integrity, availability, or in general, any other enhancement to positioning, navigation, and timing that is not intrinsically part of the GNSS itself [1].These systems were developed with the purpose of providing continuous robust and safe navigation, particularly in situations which require elevated precision, coverage or availability [2].

The advantages provided by the implementation of augmentation systems on satellite navigation are numerous. Hence, an extensive amount of varied augmentation systems have been developed.

Some of the benefits involved in using these systems include those mentioned previously, in particular, the fact that they can be used to improve accuracy, integrity and availability, increasing the safety of operation in this way. They are used to correct some of the main sources of error linked to GNSS. The main objective of using augmentation system is to improve the overall performance of GNSS constellations, obtaining position measurements of up to a few centimeters of accuracy.

Despite their potential as performance improving systems, augmentation works only against common mode, spatially correlated errors such as the ionosphere and troposphere delays. Multipath-induced errors, as well as interference-induced ones, are not common to the reference station and the user; therefore they cannot be recovered by means of any augmentation systems.

Among others, there are different types of augmentation systems used nowadays include:

- SBAS
- ABAS
- GBAS
- CORS
- IGS
- DGPS
- RTKS
- AGNSS

3.1 SBAS

SBAS, which stands for Satellite-Based Augmentation System, are used to improve the performance of a GNSS constellation by increasing both the accuracy and reliability of the information obtained from a GNSS system. It works by correcting errors associated to signal measurement and by supplying data regarding the accuracy, integrity, continuity and availability of its signals [11].

This augmentation system is useful for situations which rely on critical accuracy and integrity and essential in applications where people's lives are at stake and their safety of lives could be jeopardized by a lack of precision. SBAS is also indispensable in situations where a form of legal or commercial guarantee is necessary and GNSS is being used.

For instance, according to the standards set by ICAO, GPS does not comply with the strict operational requirements associated with some of the critical stages of a flight, such as during final approaches. Using SBAS at this point is vital to meet ICAO's strict requirements.

SBAS also plays an important role beyond the aviation sector, improving and extending the scope of GNSS applications such as farming or geodesy.

Different SBAS systems have been developed to provide a service for different countries. The most significant SBAS systems are WAAS, which is an augmentation system developed by the United States, EGNOS, developed by Europe and GAGAN, created by India. These SBAS networks together with other less significant ones can be seen in Figure 8.

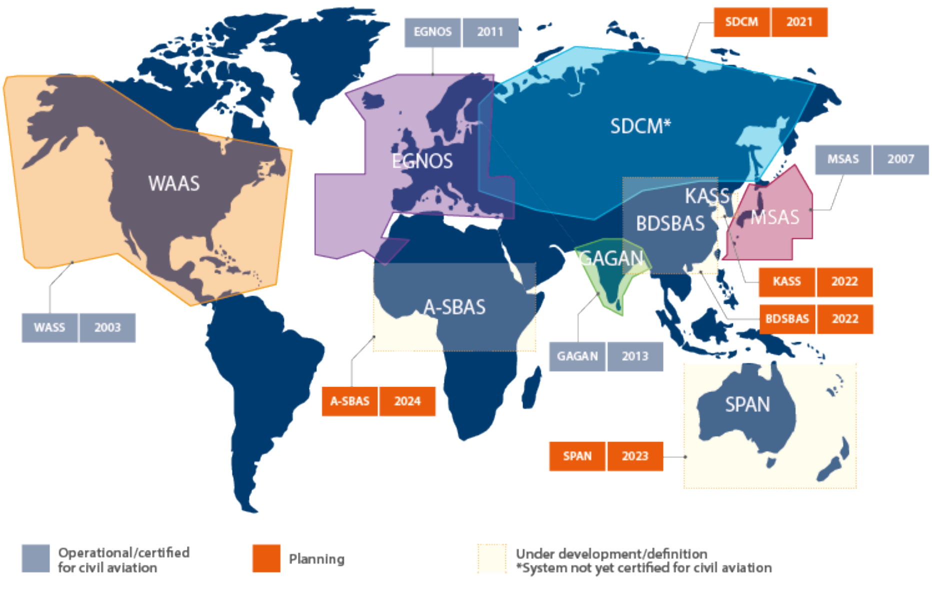

Figura 22. SBAS systems distributed around the world [11].

The different SBAS systems created can be seen more clearly in Table 8, which also includes the state of each network, in addition to the country or region that created it.

Name	Country	Status
WAAS	USA	Operating
EGNOS	Europe	Operating
MSAS	Japan	Operating
GAGAN	India	Operating
BDSBAS	China	In development
KASS	South Korea	In development
SDCM	Russia	In development
ASECNA	Africa	In development
SPAN	Australia	In development

Tabla 8: Different SBAS systems distributed around the world [11]

All SBAS systems developed must meet a global standard which states that they should be both compatible and interoperable. This means that:

- Compatible: they do not interfere with each other
- Interoperable: A user with a standard receiver can benefit from the same level of service and performance, regardless of whar coverage area they are located in.

Next, the most significant SBAS systems will be described in detail in the following subsections.

EGNOS

EGNOS is the SBAS system developed and used by the European Union. Its scope englobes most of the european territory in addition to part of the regions surrounding it.

This augmentation system is in charge of providing three different services, which are the following:

- Open Service (OS)
- Safety of Life (SoL)
- EGNOS Data Access Service (EDAS)

Available since October 1st of 2009, EGNOS OS's principal aim is to improve the achievable positioning accuracy by correcting different error sources which affect GNSS signals. These corrections aid the mitigation of ranging error sources in relation to satellite clocks, position and ionospheric effects. In addition, it is capable of detecting the distortions which affect the signals transmitted by GNSS and it can also prevent users from tracking misleading signals. This service is available free-of-charge to the public in Europe, it can be accessed by any user equipped with a device compatible with GPS/SBAS.

Regarding the second service offered by EGNOS, Safety of Life, it provides the most rigorous level of signal-in-space performance to all users of the SoL service. The primary purpose of this service is to successfully assist civil aviation operations down to minimum Localizer Performance with Vertical Guidance (LPV). This service became available the 2nd of March of 2011.

Finally, the EGNOS Data Access Service is directed at users who need accentuated performance for both professional and commercial purposes. Available since July 26th of 2012, this service is the EGNOS terrestrial data service. It offers ground-based access to EGNOS data in real time, in addition to counting on an historical archive which is only available for a set of authorised users. EDAS is basically a unique point of access for the information gathered by the EGNOS ground infrastructure distributed over Europe and part of North Africa.

Regarding its architecture, EGNOS is divided into four different functional segments:

- Ground segment
- Support segment
- Space segment
- User segment

The ground segment encloses a system of 40 RIMS, 2 MCCs, 2 NLES per GEO and the EGNOS Wide Area Network. The EWAN is in charge of providing the communication network for the elements forming the ground segment.

The particular function of each part of the ground segment will be summarized in the following list:

- RIMS: Collect data from GNSS satellites and transmit this information to the CPF of each MCC. There are 40 RIMS sites included in the configuration of the EGNOS OS, which are spread over a broad geographical area.
- MCC: These control centres receive the data obtained by the RIMS and create correction messages to enhance the accuracy and integrity of satellite signals.
- NLES per GEO: This part is in charge of transmitting the EGNOS message received from the CPF to the geostationary satellites for distribution to users, in addition to ensuring synchronisation with the GPS signal.

The system is composed by other ground support facilities in addition to the previously mentioned stations or centres. These are involved in system operations planning and performance examination, being formed by the PACF and ASQF, both operated by ESSP.

- PACF: This part provides support to EGNOS management in all aspects concerning performance analysis, troubleshooting and operational procedures.
- ASQF: Gives access to the tools used to qualify, validate and certify diverse EGNOS applications to the aeronautical certification authorities and civil aviation.

Concerning the space segment, it counts with minimum three geostationary satellites which share corrections and integrity data to GPS satellites in the L1 frequency band. This segment of the EGNOS architecture provides an elevated level of redundancy over the whole service area in case of collapse in the satellite link. The system ensures that at any point there will be at least two geostationary satellites sharing an operational signal.

Finally, the user segment of EGNOS is formed by receivers that allow their users to calculate their positions with satisfactory accuracy and integrity. In order to receive EGNOS signals, an EGNOS-compatible device must be used by the end user. At the moment, these type of compatible receivers are accessible for use also out of the aviation sector, such as in the agriculture or maritime segments.

WAAS

WAAS is another example of a space-based augmentation system. Operated by the FAA, this regional system provides support for aircraft navigation across North America by providing service in all flight phases, from take-off to landing, including vertically-guided landing approaches in instrument meteorological conditions.

Even though it was originally developed for usage within the aerospace sector, it is currently accessible for other communities, such as positioning, general navigation or timing.

It is note-worthy to highlight the fact that the service offered by WAAS can be operated together with other regional SBAS services, such as the European EGNOS, the Japanese MSAS or the Indian SBAS service GAGAN [35].

The fact that the WAAS system was designed following very rigorous standards in terms of integrity and safety, implies that users can operate with high confidence on their position estimate [36].

The architecture of the service WAAS is arranged in the following way:

- Wide Area Reference Stations
- Wide Area Master Stations
- GEO satellites
- GEO uplink subsystems

The WAAS architecture counts with 38 Wide Area Reference Stations within its structure, which receive the signals emitted by GPS satellites. These WRS sites are distributed across a vast area, and these locations are surveyed in such a way that any mistake in the received signals can be noticed.

Regarding the Wide Area Master Stations, they receive the data gathered by the WRS sites. Then, each second, the WMS generate a WAAS User Message, which contains information that enables GPS or WAAS receivers to remove mistakes from the GPS signal, improving in such a way the accuracy and integrity of the position.

The WMS then sends the messages generated to uplink stations for transmission to navigation payloads located on GEO satellites with navigational purposes. In total, the system is composed by three geostationary satellites and six geostationary uplink subsystems [36].

GAGAN

Another regional Satellite-based augmentation system that is already in full operation is the Indian GAGAN. Completed in 2011, this SBAS network was developed as a result of the cooperation between ISRO and AAI and it supports aircraft navigation over the Indian airspace in particular, with the capability of extending to neighboring FIRs.

The system's architecture is the following:

- Geostationary satellites
- Reference stations
- Uplink stations
- Control centers

More specifically, the system consists on three geostationary satellites, 15 reference stations distributed throughout the Indian territory, three uplink station and two control centres.

As the other SBAS networks, GAGAN is perfectly compatible with other SBAS systems such as WAAS or EGNOS [37].

Figura 23. Indication of the coverage offered by the GAGAN augmentation system [12]

Some of the applications for which GAGAN can be extended to, in addition to its use in the aviation sector for which it was originally designed and developed, GAGAN can be used in the scope of forest management, scientific research for atmospheric investigation of natural resource and land management, among many other compatible uses [38].

MSAS

MSAS is the Japanese version of a Satellite Based Augmentation System, similar to the previously described WAAS, EGNOS or GAGAN. It is owned and operated by the Japanese Ministry of Land, Infrastructure and Transport, in addition to the Japan Meteorological Agency, JMA.

As with the other augmentation systems in general, MSAS was designed with the objective of enhancing the accuracy, integrity and availability of measurements obtained by GNSS constellations, which have their main application in the aviation sector. In the case of MSAS, the first trials were performed with success in 2007, when the system was declared to be operational for aviation use. At this point, it provided a service which consisted on the horizontal guidance for en-route through non-precision approach.

The functioning of this augmentation system consists on the processing of information obtained by GPS satellites, which is collected by a system of stations to create a SBAS message sent to the geostationary satellites. Then, this information is broadcast to the user receivers and these calculate the position of the aircraft and communicate possible alert messages.

The architecture of MSAS is mainly formed by three different segments:

- Space segment
- Ground segment
- User segment

The space segment was already commented by detailing the amount of satellites forming the constellation. About the ground segment, it is formed by four Ground Monitor Stations which collect data on the GPS and MSAS signals. This collected information is then sent to two Master Control Stations (MCS), which are located in Kobe and Hitachiota. They then compute precise differential corrections and integrity bounds. Then, these corrections are sent back to the MSAS satellites which rebroadcast said information to the User Segment. Additionally, two Monitor and Ranging Stations complete the Ground Segment by determining the correct orbit of the satellites.

Regarding the user segment, it uses the data shared by each GPS satellite to compute its location and current time, and receives the MSAS corrections obtained from the space segment.

3.2 ABAS

ABAS, or Aircraft-Based Augmentation System shares a common objective with the previously described SBAS systems: to enhance the performance of the satellite constellation it receives data from. In this case, the purpose is to improve the measurements obtained from GNSS constellations, based on the data available on-board of the aircraft [39].

This augmentation system provides sufficient integrity as to use GPS as the main and only navigation method during the following phases of a flight:

- Take-off
- En route
- Approach
- Non-Precision approach

The most common type of ABAS is the RAIM, which stands for Receiver Autonomous Integrity Monitoring. This technique involves using redundant data obtained from GNSS in order to provide GPS data integrity. In ABAS, the additional information is obtained from certain navigation sensors which are used to compute the position of a given aircraft, or through internal algorithms used to enhance navigation performance.

In particular, RAIMs ensure the integrity and reliability of the position calculated, pointing out faulty signals in the process [40].

Another form of ABAS includes Aircraft Autonomous Integrity Monitoring (AAIM). It applies the data obtained from additional sensors found aboard the aircraft in order to facilitate GPS data integrity.

Additionally, the FDE is the part of the ABAS network deployed to detect and exclude errors from position calculations.

3.3 GBAS

GBAS stands for Ground-Based Augmentation System. It refers to any augmentation network which obtains its measurements from ground stations. According to ICAO, GBAS can be defined as .ªn augmentation system in which the user receives augmentation information directly from a ground-based transmitter [41]."

This augmentation system does not depend on geostationary satellites. It is the most used system at a local level, due to its coverage restrictions and the provided services in terms of precision approaches and position computation.

Two important examples of Ground-Based Augmentation Systems include the United States developed LAAS and the Australian GRAS.

The main aim of implementing GBAS in navigation is to allow approaches and landing operations without using an Instrument Landing System (ILS) network. Currently, the available GBAS airport facilities allow Category I, CAT-I, precision approach service, which are enabled by ICAO standards.

Regarding the architecture of a typical GBAS Ground Facility, it is normally formed by three or more GPS antennas, a central processing system, such as a computer, and a VDB transmitter. All these components are usually located locally on an airport or in its proximity [42].

Among the different benefits involved in using GBAS, the following can be highlighted:

- Provides an alternative to the conventional ILS for approaches
- One GBAS can support up to 48 different approaches
- A GBAS network covers many runway ends with a greater installation flexibility than an ILS system with localizer and glideslope antennas at each end.
- It can provide various approaches to decrease wake turbulence, leading to a better resilience and keeping availability and operations continuity.

In general, the safety requirements are more severe on GBAS systems in comparison to SBAS networks, given that the main use of GBAS is for the landing or approach phase of a flight. At this point, real-time accuracy, as well as signal integrity control, is critical, in particular during adverse weather conditions, where the visibility is very poor, or even non-existent.

III

Future Projections

Introduction

Regarding the future of air navigation in general, it is important to bear in mind that any advances made in the sector will be done taking into account the main objectives behind the concept of aircraft navigation in general.

As it has been emphasized throughout this thesis, air navigation techniques emerged mainly due to the need of developing a system that helped to improve the safety of flights, after a series of fatal incidents proved the need to design a method to guide aircraft precisely.

Hence, any developments achieved in terms of aircraft guidance, will be done with the aim of further increasing accuracy, precision and reliability of the navigation tools used, in order to increase the general safety of the operation.

In addition to ensuring the security of operations, another factor to bear in mind when developing new techniques which has become increasingly significant in the actuality is the environment. Taking into account the speed at which the aviation sector has grown over the last decades, and considering the detrimental effects it implies in terms of the environment, new navigation techniques which could cut the use of fuel and therefore the impact of the aviation on the environment are being developed.

Regarding air navigation techniques, the effects of aviation on the environment could be improved by increasing the overall efficiency of the flight by means of navigation tools. This is due to the fact that increasing precision of the route followed could reduce the kilometers covered by the aircraft, reducing in this way the fuel consumed and the emissions released into the atmosphere.

Among the strategic objectives of ICAO, which is the entity that represents the global forum of States for international civil aviation, the following can be highlighted:

1. Safety
2. Air Navigation Capacity and Efficiency
3. Security and Facilitation
4. Economic Development of Air Transport
5. Environmental Protection

These objectives were addressed in the ICAO document which represents the entity's plan for the next 15 years. In particular, this document represents the plans for the years 2016 to 2030.

1.

Development of Global Navigation Satellite Systems

Nowadays, most aircraft are guided using information provided by GNSS satellite constellations. Even though some radio aids are still operative and used in some phases of an aircraft's route or in locations where for some reason satellite navigation is not used, the current tendency is to substitute navigation operations aided by radio systems by more accurate and reliable satellite navigation systems.

Regarding actual statistics of use of GNSS in the aviation sector and predictions in the near future, at the moment, it is estimated that the use of GNSS constellations will experience an important increase both in terms of aviation and in other general uses.

In 2015, the utilization portion of GNSS in aviation applications was 6.1 % of the total professional GNSS users. This total percentage is expected to reduce until 1.5 % of the total service of GNSS by 2025. This implies that the range of uses of GNSS will increase significantly [30].

Even though the proportion with respect to the total service provided by GNSS will decrease in terms of aviation applications, the absolute numbers are expected to increase from approximately 0.9 million units in 2015 to 1.4 million in 2025, which implies an increase of 1.6 % [30].

In terms of its economic value, the GNSS market size is predicted to reach USD 386.78 billion by 2027, in comparison to a market size of USD 161.27 billion in 2019. This is due to expansion not only in the aviation sector, but in many other sectors which are starting to benefit from the potential of using GNSS constellations for varied purposes [43].

Regarding potential new uses of GNSS constellations in general, it is expected that their service will experience a rise in demand by drones, which are not included in the statistics of aviation related GNSS applications, even though they are aerial vehicles too [30].

Despite the fact that currently there are different satellite constellations used for navigation which provide service to guide aircraft through the airspace safely, there is still space for improving this technology in order to obtain an even better service.

Furthermore, given that satellites have a relatively short life span of approximately a decade, which means that they should constantly be renovated, as the oldest ones become inoperative, they must be exchanged for newer ones. This situation gives an opportunity of substituting the older satellites by new ones with better technical capabilities and enhanced performance in general.

In addition to renewing existing satellite networks in order to keep them functioning, some of the current satellite constellations are working on projects to expand them, with the objective of increasing the quality of the service they provide.

In particular, the idea of using GNSS constellations for space navigation is being studied and developed currently. The existence of GPS signals in space, which arise as a result of deflections from the main beam, has been proved to be useful for a series of purposes, however, this situation could be further exploited and used for space navigation.

An approach which could be common to all existing satellite constellations could be to increase the collaboration among different constellations in order to improve performance by interchanging measurements obtained.

As a summary of the general forecast made for the development of GNSS in the near future, it can be stated that this market is expanding in global terms, in particular in the Asian and Middle Eastern regions. Furthermore, another user which is demanding an increasing service of GNSS are helicopters, which require an augmenting service in off-shore and land procedures [30].

In addition, it can be expected for the sector to experience an increase in collaboration among different existing satellite constellations, leading to multi-constellation and multi-frequency GNSS [30].

As stated by the European Radio Navigation Plan, development and implementation of GNSS for different aviation purposes is and will be encouraged by the requirement to improve performance of ATM, efficiency in terms of the environment and economy and to increase airport capacity [30], bearing in mind the main requirements for aviation users, which include availability, continuity and integrity.

Recent developments and future projects planned for each of the main satellite constellations will be discussed in this section, starting with the GPS constellation, which was the first one to become operational.

1.1 GPS

The unprecedented success of the United States GPS system, both in civil and military applications, implies that to date, economic resources intended for modifications and further research time are being invested in the never ending development of this positioning system.

Despite the fact that it became fully operational and available decades ago, new technological advances and different performance enhancements are on their way, with the objective of providing an improved quality of service [44].

In general terms, the current plans of the United States government regarding the GPS constellation involves the modernization of the different segments of the system. This program involves acquiring a set of consecutive satellites, as well as improving the control segment, including the AEP and the Advanced Control Segment. The schedule of the program can be observed in Figure 24.

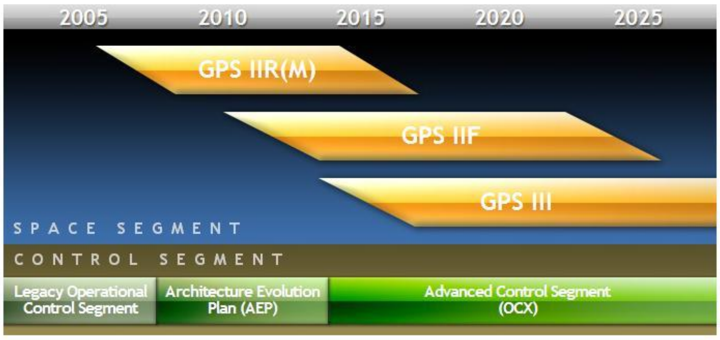

Figura 24. GPS Modernization Program Schedule, [13]

In 2018, the new generation of satellites started to take their place in the GPS constellation orbiting the Earth. The first satellite of GPS III was launched at the end of 2018, using a SpaceX Falcon 9 rocket, and satellites belonging to this block will continue to be launched until 2025. These new satellites belonging to the block GPS III present significant improvements with respect to the original satellites of the constellation. For instance, they provide an increased positioning accuracy due to the new set of atomic clocks included in each satellite.

In addition, they provide a more reliable GPS reception also in dense urban areas or indoors, given that these new generation of satellites have more transmitter power. Furthermore, they can provide a greater resistance to jamming from the signals. Additional improvements, include adaptations of these satellites in order to provide use of GPS in space navigation [44].

Moreover, one of the approaches which is planned to become obsolete in the near future with the launching of GPS III satellites is Selective Availability (SA). This measure has been used since the beginning of GPS by the military in order to limit the use of GPS by the civil public. By means of SA, the US military is able of reducing the accuracy of the measurements provided by the system [13].

In 2007, the U.S. government announced plans to permanently eliminate SA by building the GPS III satellites without it.

Another promising potential application of the GPS constellation in the near future could be its use in space navigation. Even though GPS technology was developed with the intention of using it in terrestrial navigation, it has been discovered that these signals can be used as well for space navigation, in particular, for spacecraft found as far away as the moon or during their transit to and from Mars.

Despite the fact that GPS signals are directed towards the Earth, part of them are mitigated into space. These GPS signals, which are the "leftovers.ºf the main beam, are used in space. Currently, GPS signals in space are used in the ambit of controlling the docking of material for the ISS, precise positioning of weather satellites or for other scientific satellites in general [44].

1.2 GLONASS

Regarding the Russian GNSS constellation, it is currently working on three different blocks of satellites which are at different phases of their development.

These three phases are:

- GLONASS-K2
- GLONASS-KV
- GLONASS-KM

At the moment, GLONASS-K2 is on the testing and manufacturing phase, planned to be ready for 2022, whereas KV and KM projects are longer-term plans, with GLONASS-KV being on the design phase and intended to launch satellites belonging to this block between 2023 and 2025. Regarding GLONASS-KM, it is still on the research phase, and it is planned for it to launch its first satellite by 2030.

Among the features the K2 new generation of satellites will contain, the main one that can be highlighted would be the full suite of modernized CDMA signals in the L1 and L2 bands, more precisely, th L1SC, L1OC, L2SC and L2OC, in addition to the L3OC signal. Starting in 2022, it is planned for GLONASS-K2 to gradually substitute existing satellites in the constellation [45].

In general, the objective of the GLONASS constellation is obtaining a satellite system which can provide a service of equal quality to the one provided by GPS, which to date is the most used GNSS constellation. To do so, Russian engineers and researchers will continue working on the development of their existing network, releasing into orbit new satellites, equipped with improved technologies and enhanced performance characteristics.

1.3 BeiDou

The future plans for the Chinese global constellation include a set of different projects, based on current global concerns.

For instance, one of the future projections involving the BeiDou constellation could be fixing the operating latitude of the constellation, since it works in such a way that the service provided to very high latitudes is poor or even non-existent. This is a particular concern given that global warming is leading to the melting of the polar caps over the last decades. This concerns satellites since it would be useful for global constellations to provide service over this areas in order to monitor the evolution of these polar caps [46].

This is of particular relevance to navigation since it is of vital importance to know the situation of these arctic and antarctic areas, in order to navigate safely through these continuously changing regions. A simple way of ensuring this required coverage would be by increasing the inclination of IGSO satellites of the BeiDou-3 group [46].

In general, it can be predicted that some approaches that could be taken in order to improve the service provided by the BeiDou constellation, other than increasing the inclination of the IGSO satellites to provide coverage over polar regions, could be to design new IGSO satellites capable of providing RSMS and BDSPPP services which could aid in overcoming the "south wall effects"[46].

In addition, in order to guarantee the continuity and availability of satellite orbit parameters in satellite maneuvers, the INS payloads could be included in a set of satellites. These are some of the future approaches that could be considered to enhance the performance of the Chinese GNSS system, however, as time has proven to be so, there is an infinite number of possibilities offered by GNSS constellations in terms of navigation.

1.4 GALILEO

The European GNSS constellation became fully operational in 2020, offering a global service ever since. Even though it is currently functional, there are different approaches which have been suggested in order to improve the existing service provided by this constellation or even to increase the applications it could be used for.

EGEP, which stands for European GNSS Evolution Program, is a program developed by the ESA entity currently backed by 17 members of the ESA and Canada. Its main objective is to assure the continuous growth of GNSS technology in Europe by undertaking research in all technologies associated to GNSS satellite constellations and to regional Space-Based Augmentation Systems [47].

Among the potential areas of improvement suggested by this program, the idea of improving accuracy for positioning and timing, increasing security or general service enhancements can be highlighted [47].

In terms of the main augmentation system in Europe, EGNOS, it is planned to expand this service in order to provide support for the European GNSS Galileo, in addition to GPS, which is already supported by EGNOS at the moment. This potential expanded service would use the signals emitted by Galileo in addition to the ones corresponding to the latest generation of satellites in the GPS constellation in the L5 band. These projects are planned to be introduced in 2025, with the primary aim of enhancing position accuracy, integrity and robustness [47].

1.5 Regional Constellations

Regarding the regional constellations of satellites, which instead of providing coverage over the whole world, focus their services in a particular regions, there are also future projects suggested with the intention of enhancing the service they provide.

First, the future projections of the Indian GNSS constellation will be discussed. Currently, as commented in section 2.2 of part II of this thesis work, NavIC or IRSS is formed by a total of seven satellites. As published in the 12th FYP of the country, India's Department of Space stated their plans to increase the number of satellites present in the constellation until reaching a total of eleven satellites, increasing the coverage offered by this system.

These new satellites are planned to be launched during the 13th FYP, during the years 2017 and 2022, in geosynchronous orbits with an inclination of 42º. Furthermore, the creation of atomic clocks developed by India has been started.

Among the improvements included in the new generations of satellites developed by ISRO, the fact that the lifespan of satellites has been increased to 12 years or that new payloads have been featured can be highlighted. Regarding the frequencies that will be used by these new satellites, they will feature both L5 and S frequency bands, introducing as well a new interoperable civil signal belonging to the L1 frequency band.

In addition, the Global Indian Navigation System (GINS) is a project which will be developed in the near future. The research of GINS was started as part of the initiatives suggested in India's 12th FYP. It is a project to develop a global constellation operated by India, consisting on 24 satellites orbiting the Earth at 24 000 km above its surface, in the MEO orbit [48].

The other regional constellation which was discussed in section 2.2 of part II of the thesis is the Japanese Quasi-Zenith Satellite System. In this subsection of the project, the future projections being studied in order to improve the service provided by this system will be discussed.

Currently, QZSS works in cooperation with the United States satellite constellation GPS, so the main focus regarding future developments of the Japanese system is to obtain an independent network of satellite constellations for navigation by 2023.

This constellation, totally independent from the American GPS, would consist on a total of seven satellites, including the four current satellites used with three additional ones, with launch dates considered between 2023 and 2024. Among the plans of this program, the replacement of the satellite QZS-1 by new QZS-1R in 2021 is included [34].

2.

Single European Sky

Another navigation approach which has been considered since a couple of years ago, is the Single European Sky (SES). This measure consists on the de-fragmentation of the European airspace, which is currently distributed according to the different countries in Europe. It seeks to reform the air traffic management system present in Europe through a set of actions performed in the following four different levels [14]:

- Institutional
- Operational
- Technological
- Control and Supervision

The idea behind this approach arose due to the unprecedented growth of air traffic experienced in the early years of the century. With the objective of being able to cope with air traffic growth and operations involved with the required safety, the project of the Single European Sky emerged [49].

The fact that European air spaces are some of the most transited in the world and that the currently used system of air traffic management lacks the required level of efficiency, encouraged the development of this project.

At the moment, European air traffic management is controlled by member countries of the European Union, which cooperate by means of the intergovernmental organisation Eurocontrol, which includes most European countries [14].

Among the different advantages that this measure could provide, the following can be highlighted:

- Increased flight efficiency
- Reduced costs
- Environmentally friendly conditions
- Reduction of delays
- Increased safety standards

This measure bears in mind the increasingly importance of the environment, since cutting delays and providing shorter routes for most flights, could reduce aircraft emissions, reducing in this way the impact of aviation on the environment.

The current distribution of the European airspace and the presence of national borders, implies that in some cases, for instance during strikes of air traffic controllers, aircraft are forced to follow longer routes, burning additional fuel in this way. Aircraft travel an average of 49 additional kilometers than the necessary to perform a given route due to this distribution of the airspace [14].

The intention is to expand the SES approach to other third countries neighboring the frontiers of the European Union. This objective mainly depends on the policy of the EU in terms of international relations.

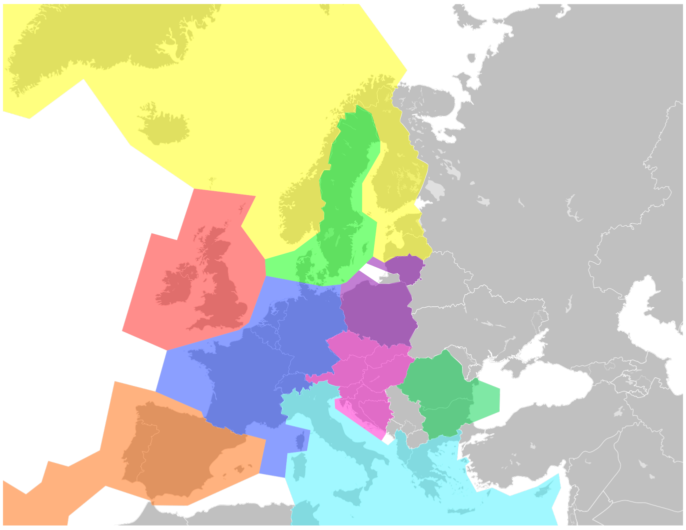

Figura 25. Functional Air Space Blocks, [14]

The different blocks into which the European airspace is distributed according to the different countries involved can be seen in Figure 25.

The idea behind the Single European Space program emerged in 1999 and the framework regulation that enclosed the working methods of the program were adopted at the end of 2003, entering in force on 2004 [14]. Since then, it has been divided into different phases, which include the following:

- SES-I (2004-2009)
- SES-II (2009-2012)
- SES 2+ (2013-2018)
- Amended SES 2+ (2019-present)

The Gibraltar Issue slightly hindered the development of this program, since the fact that Spain impeded the inclusion of Gibraltar Airport in the SES program, implied that the whole development had to be temporarily suspended in 2000. However, the completion of the Brexit in 2020, implied that this block of the program could be removed from it [14].

IV

Practical Application

Description

After introducing a theoretical background of all the navigation aids used currently in air navigation throughout the first three sections of this end of bachelor thesis, a more practical approach will be followed in this final part, suggesting a potential technique which could be followed in order to enhance the effectiveness of air navigation, specifying a particular route which will be used to detail the implications of this practical application.

Throughout the previous sections of this thesis, both the historical evolution of different aids in the aviation sector and their current uses have been discussed. Hence, the knowledge obtained throughout this theoretical research will be applied in order to emphasize the utility of such methods and technology in the current aviation sector, with the objective of supporting the theoretical study of air navigation performed.

In addition, with this section of the thesis, it is intended to suggest a new relatively simple approach which could be applied in the near future of aviation in terms of air navigation, in order to optimize the performance of sector regarding navigation capabilities. In particular, the performance improvements in terms of the different environmental consequences implied will be discussed, given the increasing concern and importance of impact on the environment in the current aviation situation.

In order to develop this section of the thesis, the use of the following platforms or software will be required with the objective of obtaining the relevant parameters required, which will be detailed in the following pages of this section.

- Simbrief by Navigraph [50]
- Route Finder [51]
- Microsoft Excel

1.

Route Definition

As previously mentioned, in order to aid the explanation of the idea behind the practical application defined in this thesis, a real route will be defined with the intention of providing an example of the potential of this application.

The route selected in this case is the flight departing from Miami International Airport and landing in Adolfo Suárez Madrid - Barajas Airport. This particular route was selected due to the fact that it is a transatlantic route in which the effects of optimizing navigation methods can be appreciated to a greater extent due to its large length and duration.

In order to determine the actual route followed by aircraft flying from Miami to Madrid, the platform Route Finder"was used with the objective of determining the waypoints included in this route. Then, the platform "Simbrief by Navigraph"was used to represent this particular route, visualizing in this way the waypoints involved in an actual map. This representation can be seen in Figure 26.

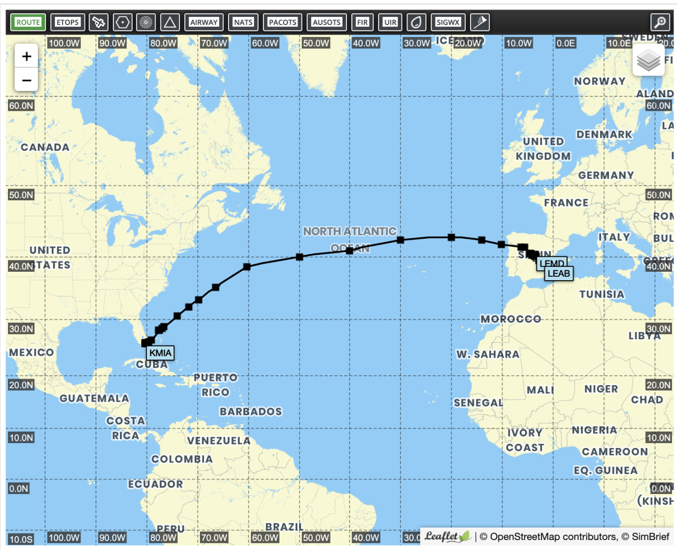

Figura 26. Representation of Miami-Madrid transatlantic route by Simbrief

Another approximate representation of the route followed including some of the waypoints involved was represented using the platform Excel from Microsoft Office. In this case, the particular longitudes and latitudes of the hypothetical waypoints which could be followed in the loxodromic route from Miami to Madrid were calculated using the corresponding formulae and obtaining the result observed in Figure 27.

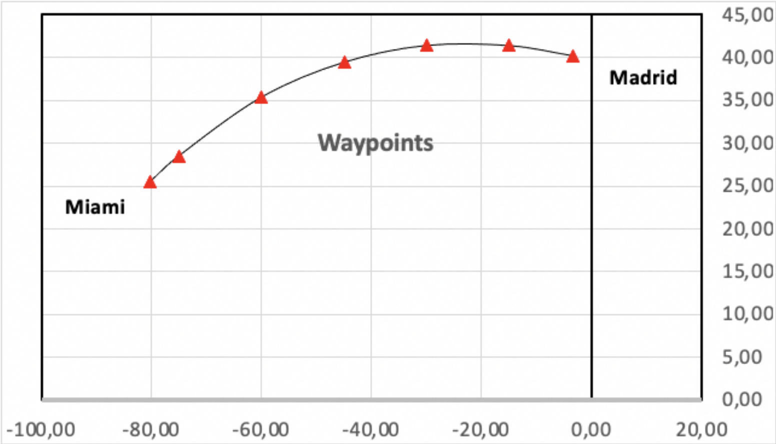

Figura 27. Representation of the Miami-Madrid orthodromic route using Excel

This graph obtained using Excel represents the orthodromic route which joins Miami and Madrid airports. Some of the potential waypoints that would divide said route into different legs have been represented by means of a red triangle. These waypoints have been calculated to have a separation of 15º of longitude within each other, which is a reasonable suggestion considering the actual waypoints used in these routes.

The conclusions that can be drawn from the comparison of the route representations obtained using the two different platforms mentioned above (Simbrief by Navigraph and Microsoft Excel) include the fact that, as seen from a first glance, the two routes differ slightly, since the curve of best fit joining the waypoints in Figure 26 is not as smooth as the one in Figure 27. This is due to the fact that, as previously commented, the graph plotted in Excel represents the orthodromic route, whereas the Simbrief visualisation is a representation of a real route.

In order to explain this slight differences, it is important to highlight the fact that navigation between two points usually involves following the orthodromic path between them, since this is the shortest route that can be followed. An orthodromic line corresponds to the great circle joining two different points.

However, in air navigation, in most cases an orthodromic route is divided into a set of different loxodromic 'legs', which are paths joining waypoints. A loxodromic line is a line above the Earth's surface that cuts all meridians by the same angle and they are represented using straight lines in a Mercator card. Since they provide a constant course, these lines are followed for simplifying purposes, and it is relatively efficient if these legs are navigated efficiently.

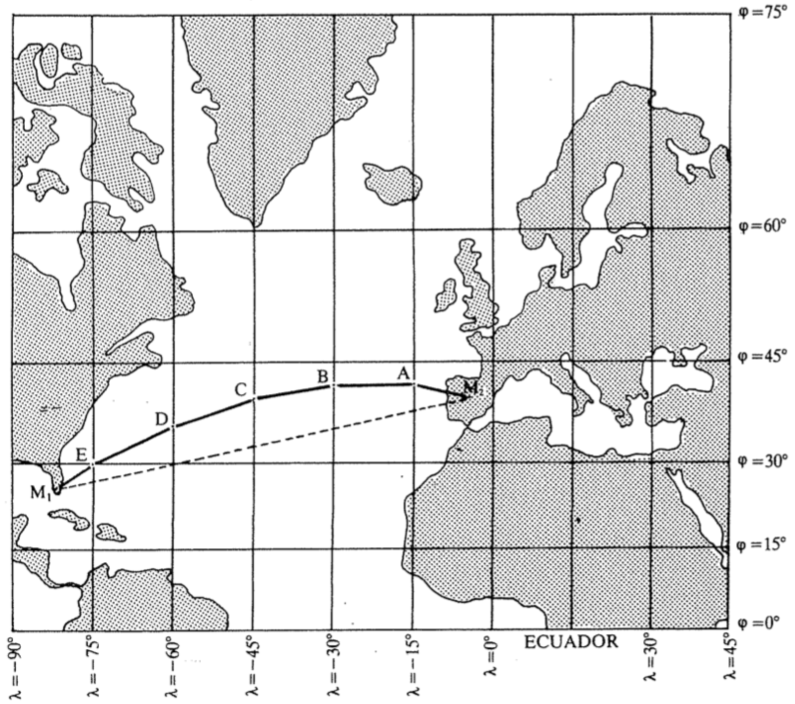

Figura 28. Comparison of the orthodromic and loxodromic lines joining Miami and Madrid.

Figure 28 represents the situation described where an orthodromic route is divided into different short loxodromic lines, using the route of choice for this application (Miami - Madrid) as an example to illustrate this navigation method. In this case, the smooth curve joining directly points M1 and M2 represents the orthodromic route, seen as a curve in the Mercator projection. On the other hand, the short, straight lines M1-E, E-D, D-C, C-B, B-A and A-M2 represent loxodromic lines, seen as straight lines in the Mercator projection.

2.

Proposed Solution

The problem with this navigation method arises following the fact that waypoints are typically located at intervals with a length ranging between 500 and 1000 kilometers. This implies that the pilot receives no additional information between waypoints, which should not be necessary, since the airways are well defined. Despite this fact, not receiving additional guidance between waypoints leads to these airways or legs joining being wider than necessary, and this can lead to the aircraft covering a longer distance, which at the same time results in a surplus fuel consumption and the emission of additional exhaust fumes increases too, among other detrimental consequences for the environment.

Hence, as a part of this thesis, a navigation system were this issue could be tackled is proposed. The general concept behind this suggestion is to implement a system which, using information from satellite constellations used for air navigation, GNSS, provided non-stop, continuous feedback to the aircraft in order to ensure that it is following the correct route, rather than relying on the position of the established waypoints.

In this way, the length of the route would be optimized, ensuring that the shortest distance possible is being followed at any point.

Again, the platform Excel has been used to represent how the route would change if information was provided in a more continuous way. This has been accomplished by locating waypoints at intervals of 5º of longitude with their corresponding latitudes, instead of every 15º, as done in the previous representation. This provides a more continuous flow of information, which could be further increased by locating waypoint in smaller intervals, for instance, for every 1º of longitude covered.

The route with 5º longitude intervals can be appreciated in Figure 29 below.

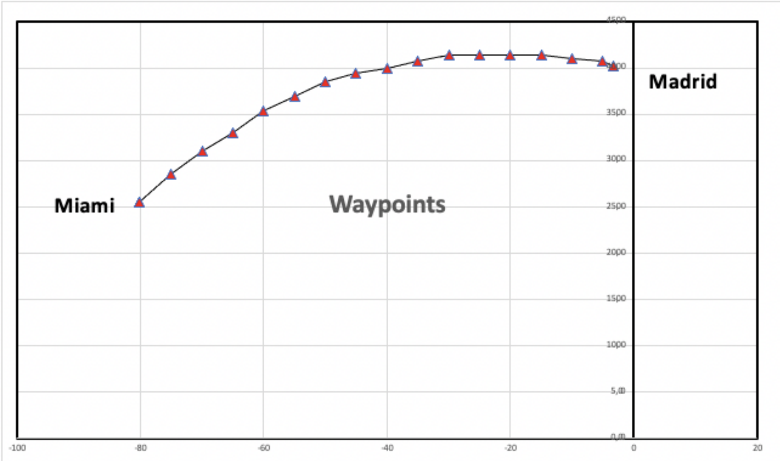

Figura 29. Representation of the Miami-Madrid orthodromic route using Excel

As it can be concluded if Figures 27 and 29 are compared, by increasing the number of reference points, the distance covered between them is reduced significantly, which implies the fact that it is easier to follow these lines without covering additional distances arising from mistakes due to lack of guidance information.

In the next figure, both graphical representations from Figures 27 and 29 have been overlapped, in order to obtain a comparison of the route with the different number of waypoints that have been suggested.

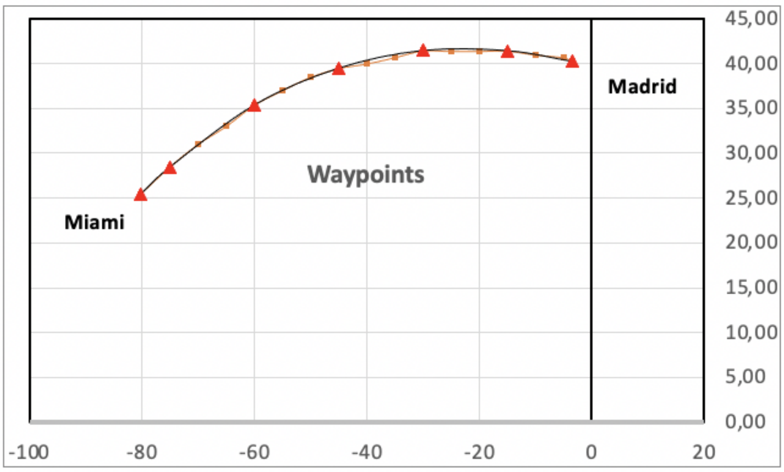

Figura 30. Comparison of the routes obtained using Excel

Overall, by using a navigation system such as the one proposed and described in this section to guide aircraft, the route followed could become more adjusted to the original orthodromic path between two different points, providing narrower airways as well as various benefits for the environment, including the reduction of gas emissions and reducing fuel consumed by aircraft in any given route.

Taking into account that on average, an aircraft emits 63 of carbon dioxide per kilometer and passenger [52], reducing the distance covered during a particular route to any extent would lead to a very significant effect on the environment, since a route such as the described in this section, from Miami to Madrid, covers approximately 7000 kilometers. Considering a relatively large aircraft with capacity for 200 passengers, and taking into account the average emissions detailed previously, this route would imply the emission of around 88 2000 000 grams of carbon dioxide. Hence, any slight reduction in the distance covered would lead to a significant improvement in terms of the emissions released into the environment, which must be taken into serious consideration.

Conclusions

Throughout the realisation of this End of Degree Thesis, the objectives proposed in the initial description of the document have been met satisfactory and overall it can be stated that the project was a success, since in addition to fulfilling the suggested objectives, the knowledge associated to the topics relevant to this Thesis were expanded and properly settled, covering a set of additional topics which were considered to be suitable in relation to the Thesis' main field of discussion.

The importance of implementing actual and developed systems to guide aircraft has been highlighted throughout the realisation of this project, stating examples of situations where the lack of proper navigation systems has led to catastrophic outcomes, particularly prior to the integration of GNSS satellite constellations in the navigation sector.

Currently, governments and airlines in general have realised the fact that it is vital to invest in the research, development and implementation of proper navigation techniques in order to ensure the safety and well-being of the passengers and crew members of aircraft in all situations. The trend in the sector is to use the most reliable method, which has been proven to be using GNSS constellations, in spite of more rudimentary and outdated alternatives which were used several decades ago.

Due to the investment of time and resources in this constantly evolving sector of the aviation environment the reduction of navigation related accidents and incidents has been made possible. Keeping track of the new relevant technologies is mandatory in order to continue evolving and expanding the aviation industry.

Overall, the realisation of this Thesis has made clear the fact that the situation in the aerospace sector in general would not be possible without the development of the sophisticated navigation technology and methods used, in particular satellite navigation systems, which not only benefit the industry of air navigation, but have a broad range of indispensable uses in today's society.

Budget

Lastly, an estimate of the costs implied in the elaboration of this End of Degree Thesis will be provided, including material costs and human resources.

	Time (h)	Unit Cost (€/h)	Total Cost (€)
Student	85	12	1.020,00

Tabla 9: Costs related to bibliographical research

	Time (h)	Unit Cost (€/h)	Total Cost (€)
Student	270	12	3.240,00
Tutor	12	30	360,00
Total			3.600,00

Tabla 10: Costs related to the bibliographical analysis and the elaboration of the Thesis

	Time (h)	Total Cost (€)
Computer	355	1.300,00
Electricity	355	20,00
Total		1320,00

Tabla 11: By-product costs of elaborating the Thesis

	Gross Total (€)	VAT(21 %)(€)	**Net Total (€)**
Cost	5.940,00	1.247,40	**7.187,40**

Tabla 12: Total Net Costs involved in the elaboration of the Thesis

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